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# The physical properties of white dwarfs in cataclysmic variables

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Since the advent of Gaia combined with Hubble Space Telescope COS and STIS spectroscopy, extensive new physical properties of accreting white dwarfs in cataclysmic variables have been obtained. This review is focused upon new robust white dwarf masses, as well as surface temperatures, chemical abundances and rotational velocities of accreting cataclysmic variable degenerates. We find that the N/C anomaly and supra-solar abundances of Al are present both in CVs with evolved donors and CVs with unevolved donors. Our results up to now are summarized along with phyiscal interpretations.

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## Introduction

This paper is the manucript version of an invited talk that was presented at the Golden Age of Catacysmic Variable conference in Palermo (Sicily) Italy in September of 2023. The paper is organized as enumerated by five sections: I. A Brief History of the First Exposed CV White Dwarfs; II. Precision CV White Dwarf Masses and Precision Surface Temperatures: The Gaia Era + HST; III. Chemical Abundances and Rotational Velocities of White Dwarfs in Cataclysmic Variables; IV. The prototype of the Z Cam class of DNe: a gift from FUSE; V. Conclusions.

## 1. History of white dwarfs in cataclysmic variables

The mechanism of Cataclysmic variable explosions and the kind of star that exploded was unknown until the work of Evry Schatzman [1] and Leon Mestel [2], who attributed the classical nova explosion to the ignition of hydrogen in electron degenerate layers. Not long afterward, the bright dwarf novae, U Gem, SS Cygni, and AE Aquarii (originally classified a dwarf nova) were being extensively observed but the underlying causation of their variable optical brightness states was unknown. As reported in [3], statistical studies by [4] and [5] noted that post-novae have absolute magnitudes that cluster around Mv∼4 while dwarf novae in quiescence have absolute magnitudes that tend to cluster around Mv∼7.5, from which they reasoned that the hot primary components of CVs must be high gravity stars, either WDs or hot subdwarfs. Several years earlier however, the first mention that the hot blue primary components of dwarf novae were accreting WDs was in a classic paper by [6] on AE Aquarii. By the mid-1950s, the basic structure of a CV was widely accepted: a compact binary (with an orbital period≤ 1 day) in which the primary, a 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 strongly magnetic systems (polars), the WD magnetic field disrupts the formation of a disk and channels accreting gas onto the magnetic poles of the WD, while in intermediate polars, the WD field strengths tend to be lower than in polars and an outer disk forms but is truncated at the magnetospheric boundary where the ram pressure of the incoming stream just balances the magnetic pressure of the WD's field strength.

The first direct spectroscopic detections of the accreting WD photospheres in CVs were carried out in the ultraviolet using the International Unltraviolet Explorer spacecraft in 1984 by [7] and [8] for the dwarf novae U Gem and VW Hyi, respectively. The first spectroscopic detection of the accreting WD at optical wavelengths was due to [9]. They pointed out that the broad wings flanking the disk emission lines in the nova-like variable MV Lyrae during a very deep low optical brughtness state were not Doppler-broadened but in fact were the pressure-broadened Balmer wings of the WD!

Among the magnetic CVs, the first spectroscopic detection of the underlying white dwarf in a polar was presented by [10], during a low state of AM Her. This was confirmed by [11]. Later, [12] and [13] carried out UV spectroscopic analysis of AM Herculis during its low optical brightness state, revealing that the accretion cap did not cool appreciably during the low state.

The first sample of robust CV WD masses was compiled in a benchmark paper by [14] who selected those CV systems in the Ritter and Kolb CV catalog [15] with tabulated WD masses (116 out of 856 cataloged CVs) and dropped those CV WD masses that had no error estimates. Their final list consisted of 32 CV WDs deemed to have robust masses of which 22 of the systems were in eclipsing binaries. As we will see in section II, a new era of research on WDs in CVs emerged with the appearence of precise parallax distances measured with the Gaia spacecraft.

## 2. Precision CV white dwarf masses and precision surface temperatures: the Gaia era + HST

With the availability of Gaia parallaxes and high quality UV spectra with HST, it has become possible to determine CV WD masses from HST spectroscopic observations of exposed WDs in CVs with unprecedented precision. This spectroscopic method has emerged as a means of determining reliable CV WD masses (e.g., [16,17]). If a best-fitting model photospheric spectral fit to the absorption lines and continuum of the exposed WD is achieved, then a degeneracy in the solution, namely $T_{\rm eff}$ is a function of log g, must be removed. This is accomplished by scaling the model flux, $F_{mod}$, to the observed flux distribution, $F_{obs}$. The normalization or "scale" factor,S, is defined by

$$S = 4\pi \left(\frac{R_{\rm wd}}{d}\right)^2 \tag{1}$$

Thus,

$$F_{obs} = 4\pi \left(\frac{R_{\rm wd}}{d}\right)^2 F_{mod} \tag{2}$$

which yields S for the best-fitting model by using the Gaia (eDR3, DR3) parallax distance to solve for the WD radius $R_{\rm wd}$. With $R_{\rm wd}$ known, one uses an appropriate non-zero temperature mass–radius relation, preferably from evolutionary models, to obtain the mass of the CV WD with an accuracy of ~5% ([16,17]).

Assuming that compressional heating alone determines the $T_{\rm eff}$ ([18,19]) the accretion rate follows from

$$T_{\rm eff} = 1.7 \times 10^4 K \left(\frac{< \dot{M} >}{10^{-10}}\right)^{0.25} \left[\frac{M_{\rm wd}}{0.9 M_\odot}\right] \tag{3}$$

The comprehensive work by [16] represents a culmination of the new science accomplished with the largest ever sample of CV WDs having Gaia parallaxes and precision CV white masses——a sample size of 89 CV WDs. i Comparing the distributionof CV white dwarfs above and below the period gap (a gap between orbital periods of 2 and 3 hours where very few CVs are found), a surprise emerged. Even with the largest sample yet of reliable CV white dwarf masses, there is no apparent difference bewteen the average mass of CV WDs above the gap, ($0.81^{+0.16}_{-0.20} M_\odot$) and below the gap, ($0.81 \pm 0.16 M_\odot$). Since there is a growing consensus that CVs evolve from being above the gap (and younger) into older CVs below the gap, this result is indeed puzzling since nova explosions appear to eject virtually the entire accreted envelope. Moreover, nova shell abundances reveal that even part of the heavy element core is carried away by the ejected shell. The central question is: do CV WDs gain more mass than they eject in nova explosions or lose more mass than they gain with time through nova explosions? One would expect a mass difference.

At the present time, there is currently a disparity between the number of precision CV WD masses above the gap (only 21 systems) versus below the gap (68 systems). Second, of the CV WDs in the sample, there are only 5 CVs with $M_{\rm wd} < 0.5 M_{\odot}$, amounting to only 6%±4% of all CV WDs. The overall average CV WD mass turns out to be $0.81^{+0.16}_{-0.20} M_{\odot}$ which notably, as in the past, is substantially higher than the average mass ($0.60 M_{\odot}$) of isolated, non-accreting WDs ([14,16]). [16] found evidence that CV systems with orbital periods shorter than 3 hours, show an anti-correlation between the mass accretion rates and the mass of the WD, which implies the presence of an additional mechanism of angular momentum loss that is more efficient the lower the mass of the WD. [16] also noted that CV systems above the period gap are hotter and accrete at a higher rate than CV systems below the period gap, thus confirming the same finding by [20] who used the entire IUE archival sample of UV spectra of exposed CV WDs.

## 3. CV WD photospheric chemical abundances and rotational velocities

The chemical abundances and rotational velocities of WDs in CVs have been derived largely from high quality HST and FUSE spectra. The observed metal lines are fitted with NLTE model atmospheres with rotationally broadened theoretical line profiles. For the most part, the S/N is just high enough to determine reliable individual chemical abundances.

Obviously, the most important abundances are N and C since their anomalous abundance ratio signal explosive CNO processing in the past. Accordingly, we have used the following spectral features to determine the N/C ratio. For SU UMa's, we used the dominant N I (1492) absorption line, for hot WDs as in DW UMa, we used the N V (1238, 1242) doublet while for intermediate temperatures like RX And, N III (1183.0 & 1184.6) doublet. For all of the systems that reveal evidence of CNO processing, the N/C ratio ranged between 100 and 1000.

A good example of the WD temperature and gravity fit together with the abundances/rotational broadening technique is presented for the case of the exposed WD in GZ Cet in Fig.1, taken from [17]. A grid of NLTE theoretical models was constructed with H and He fixed at their solar values while allowing the abundance of each accreted element to vary from an extremely low abundance (such that no line features due to metals appear) to an extreme metal-rich abundance of 20 times solar. In the upper graph we derived the temperature and gravity of the WD, in the lower graph we derived the abundances and rotational velocity of the WD.

Results for the prototypical system U Gem were obtained in [21], revealing the presence of a slowly rotating, massive WD with $M_{\rm wd} = 1.1 - 1.2 M_{\odot}$ ($log(g) = 8.8$) and $V_{rot} sin(i) = 100$ to 150 km/s, confirming the previous results of [22] and [23]. The supra-solar nitrogen abundance with the sub-solar carbon abundance further confirms the anomalously high N/C ratio observed in previous spectra of U Gem in quiescence that has been attributed to past CNO processing [22,24]. The Roche lobe-filling donor companion of the U Gem WD does have subsolar carbon. It is noteworthy that a double absorption feature near 1669 Å could to be due to supra-solar Ar III although we cannot rule that is due to some other unidentified element (producing absorption lines in the stream material veiling the WD near orbital phase 0.6-0.8). If the identification of suprasolar Ar III is correct, then this would be further confirmation of the buildup of heavy elements associated with the extremely hot (explosive) CNO processing of a nova with dominant proton captures outside the CNO bi-cycle.



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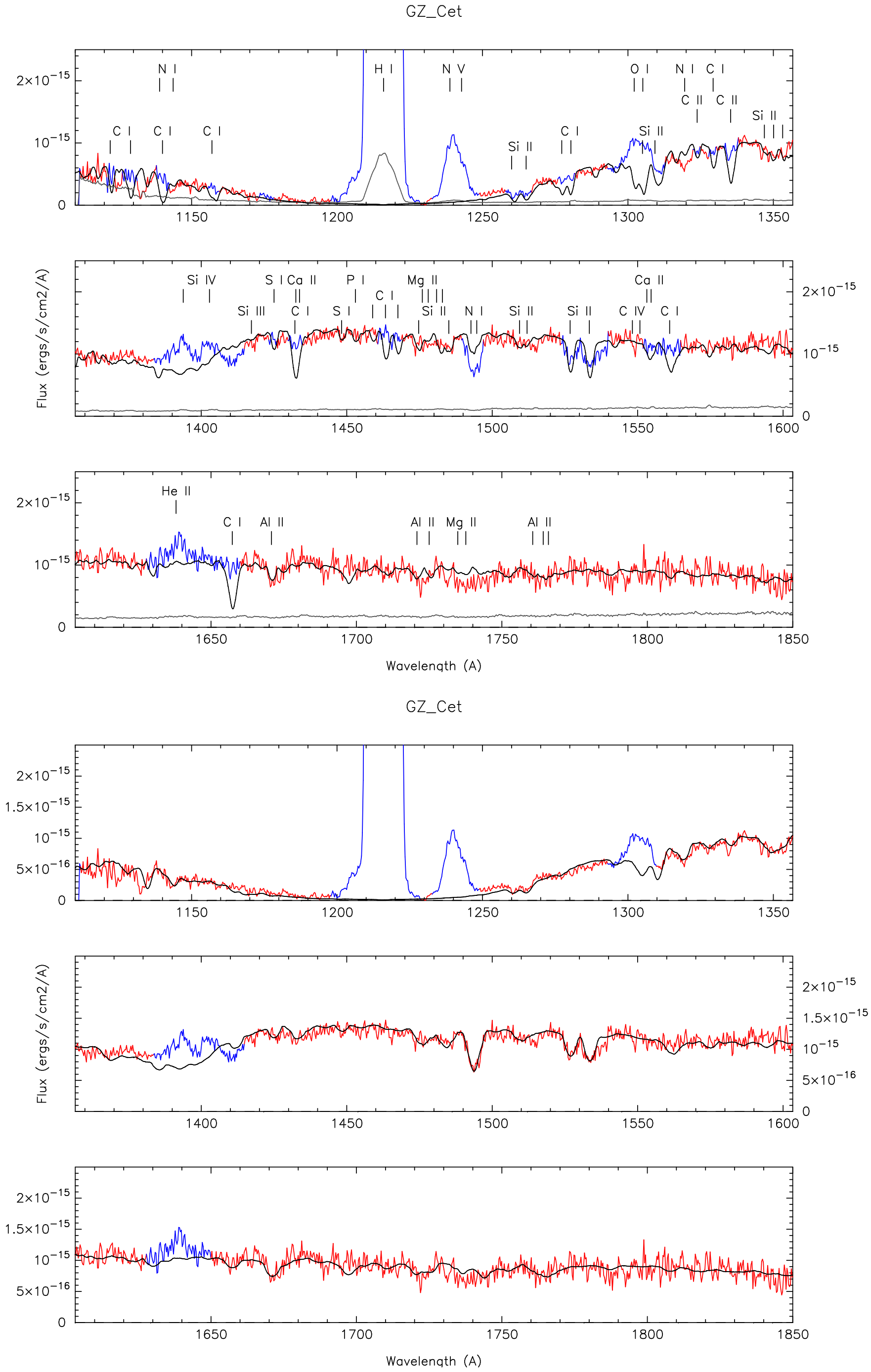


**Figure 1:** The HST/COS spectrum of GZ Cet (in red) is fitted with WD model spectrum (in black). The error is in grey and the blue segments have been masked (omitted) before the fitting. The COS spectrum from 1110 Å to 1850 Å is displayed on 3 panels. **Upper graph,** with line identifications. Only the continuum is fitted to derive the gravity and temperature of the WD. **Lower graph.** The absorption lines have been fitted to derive abundances. For $E(B-V) = 0.013$ and a Gaia distance of 301 pc, the fitting yields $T_{\rm wd} = 14,430 \pm 276$ K, $log(g) = 8.009 \pm 0.160$ (corresponding to $M_{\rm wd} = 0.615^{+0.088}_{-0.083}$), with abundances: [C]=0.01±0.005, [N]=15±1, [O]≈0.01, [Mg]=3±1, [Al]=3±0.5, [Si]=1.0±0.2, [P]≈0.01, [Ca]=0.1±0.05. To fit the dominant Si and N absorption lines, the rotational velocity was set to 500 km/s.

That being said however, the Ar III detection, is more likely to be associated with explosive CNO burning in an ONeMg core WD.

On the other hand, a system like VW Hyi has a donor companion with normal (solar C) CO features ([25,26]) raising the possibility that the accreting WD itself is responsible for the CNO-processed abundances ([N/C]≈10) and proton capture elements like Al in the WD photosphere ([27,28]). Both the normal outbursts and superoutbursts of VW Hyi cause mixing episodes in which the metals associated with explosive nucleosynthesis are brought to the surface, thus providing a possible alternate pathway for CNO-processed material to show up in the WD photosphere of some, if not all CVs. This would explain the episodic high abundance of P in VW Hyi's atmosphere [29] and possibly, if correctly identified, the high Ar III abundance in the atmosphere of the U Gem WD [21].

The most telling characteristics of the abundances we have determined are their sub-solar metallicity values for some elements (e.g., O, Si, and P), suprasolar abundances in other elements (e.g., Fe, N, and Al) and variations in the mix of differnet ion species from system to system. If the replacement time of the accreted atmosphere is shorter than the diffusion timescales of the accreted ions, then the surface abundances would tend to reflect the composition of the infalling matter from the donor star. There is little reason to expect the secondary donor stars to have sub-solar metallicity, with the exception of subsolar carbon from CNO processing. Rather, one expects that the effects of diffusion are, for the most part, responsible for these subsolar abundances. At temperatures below 20,000 K, radiative forces levitation of the ions is unimportant. Therefore, we are confident that the detected metals are the result of gas accretion onto the WD from the donor star via an accretion disk.

## 4. The prototype of the Z Cam class of DNe: a gift from FUSE

Among the dwarf novae is the subclass of Z Cam systems. While the Z Cams undergo outbursts followed by a rapid decline to quiescence typical of other dwarf novae, they occasionally, following a dwarf nova eruption, enter a state of constant luminosity about one magnitude below the peak of the outburst. This state is known as a "standstill", and can last for days to months (see [3,30]).

It is noteworthy that the prototype system Z Cam itself has a confirmed detected nova shell ([31,32]). It may be associated with a nova first reported in 77 BCE by Chinese astrologers. A second Z Cam system AT Cnc also has a confirmed nova shell by [33] with an estimated age of 330 +135/-90 yrs. This nova shell was analyzed in more detail by [34].

Unfortunately, there is no HST UV spectrum with COS or STIS of Z Cam in the MAST archive. Fortuitously however, it was observed with FUSE [35]. Their analysis was pre-Gaia, included a new but pre-Gaia mass for the WD, excluded an abundance analysis of its rich absorption line spectrum, or a rotational velocity V sin(i)for the accreting WD. Our preliminary results reveal that nitrogen has an abundance of at least 20 times the solar value and a low carbon abundance of less than one tenth solar. The CNO processing could have occurred when the donor star was previously more massive or the CNO processing occurred during repeated nova explosions of the accreting white dwarf which contaminated the donor star's atmosphere and the donor is transferring the CNO processed material back to the white dwarf. Our analysis will be reported in due time [36].



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## 5. Conclusion

It was a considerable surprise to us that we found evidence of CNO processing [17,37,38,39], not only in systems with evolved donors but also in systems with unevolved M dwarf donors. This would seem to contradict the theoretical expectation that only evolved donors were previously more massive and hence hot enough to undergo CNO processed material from the peeled-away core now being transferred to the WD. Moreoever, the systems with unevolved donors and those with evolved donors all reveal suprasolar Al, an element strongly associated with substantial production in classical novae! The CV systems with evolved donors with suprasolar Al are V485 Cen, GZ Ceti, QZ Ser, and EY Cyg with N/C∼100 - 1000. Those systems with unevolved donors and suprasolar Al are BW Scl, SW UMa, BC UMa, VW Hyi N/C∼100, a somewhat lower N/C ratio than the systems with evolved donors. While this unexpected result raises the N/C anomaly exclusively originates from the peeled-down, CNO-processed core of a formerly more massive, evolved donor, it also lends support to the nova contamination scenario [27]. It is possible that in many CV binaries that more than one channel is at work to produce the observed anomalous abundances in the WD and/or donor secondary star.

The rotational velocities of the CV WDs in our enlarged sample [17,37,38,39] reveal no surprises relative to earlier smaller samples of CV WD rotations rates. Our entire sample is characterized by decidedly sub-Keplerian rotational velocities (< 20% Keplerian). The average rotational velocity for systems above the period gap and below the period gap are the same. The range of velocities lies between a lower extreme of 40 km/s (GW Lib) to an upper extreme of 800 km/s (AL Com). Nevertheless, their rotational velocities are faster by at least an order of magnitude or more than the slow rotational velocities ($V sin(i)$ < 30 km/s), [40] of isolated degenerates. This provides clear evidence that significant angular momentum over time is being accreted along with the gas flow onto CV WDs. Looking ahead, a much greater body of chemical abundances in the surface layers of CV WDs as well as more rotational velocities and CV WD masses will be emerging from HST spectroscopy of an ever larger number of CV WDs, than the modest sample summarized here.

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