New Insights On Cataclysmic Variables From HST Spectroscopy

E. M. Sion
Department of Astronomy and Astrophysics, Villanova University, Villanova, PA 19085

Abstract Within only the past decade, an entirely new avenue in cataclysmic variable (CV) research has emerged with the first ground-based and space-based spectroscopic observations of the underlying white dwarf accretors (the *explosive central engines*) in cataclysmic variables. These spectroscopic detections have opened new frontiers of investigation into the accretion physics in the accreting white dwarf envelope, angular momentum transfer, and CV evolution. The AAVSO has played a critical role in these investigations through its ongoing optical database and the careful monitoring by AAVSO observers of changes in the brightness states of cataclysmic variables. Hubble Space Telescope (HST) studies of U Geminorum and VW Hydri, in close coordination with AAVSO data, have led to significant new advances in how matter from the accretion disk enters the white dwarf, how the white dwarf responds to the injection of mass and energy, and how the chemical abundances at the white dwarf surface hold important new clues in understanding CV evolution.

1. Introduction

Within only the past decade, an entirely new avenue of cataclysmic variable research has emerged with the first ground-based and space-based spectroscopic observations of the underlying white dwarf accretors (the "explosive central engines") in cataclysmic variables (cf. Panek and Holm 1984; Shafter *et al.* 1985; Mateo and Szkody 1984) during dwarf nova quiescence and the low brightness states of nova-like variables and magnetic cataclysmics (see the excellent reviews given by Warner 1995; Cordova 1995). These spectroscopic detections have opened a new window on the accretion physics in the stellar envelope, angular momentum transfer, and CV evolution. The fundamental astrophysical importance of observing the central white dwarf in a CV lies in the following areas:

(1) The rotation rate of the CV white dwarf provides insight into the angular momentum transfer by accretion, the spinup and spindown timescales of an accreting star, the mystery of why virtually all CVs have boundary layer luminosities far below their disk luminosities, and the key to understanding observed photometric periodicities and soft X-ray/EUV quasi-periodic oscillations;

(2) The chemical abundances of a CV white dwarf atmosphere provides insight into the envelope physics (gravitational and thermal diffusion of the accreted matter, convection, dredge-up, shear mixing and its associated turbulent forced convection, the degree of processing in the mass-transferring secondary and the thermonuclear history of the white dwarf itself and compositional relics of ancient novae—see below);

(3) The accretional heating and observed responsive rate of cooling of the CV

white dwarf may reveal the physics of the heating mechanism—whether boundary layer irradiation, compressional heating, or shear mixing luminosity—reveal the detailed physical geometry of accretional heating whether tangential via a belt or radial, test the disk instability theory which predicts an increasing far UV flux during the quiescence of a dwarf nova, test the inner disk evaporation model of Meyer and Meyer-Hofmeister (1994), reveal whether the heating over time will affect the timescale to thermonuclear runaway (TNR), since the distribution of mass, energy, and angular momentum in the accreted + white dwarf mass determines when a TNR occurs;

(4) The multi-component synthetic spectral fitting of the CV white dwarf can reveal the existence of an accretion belt—a gradient in chemical abundance, temperature, and differential rotation as a function of latitude across the white dwarf surface—and mixing/dredgeup and spinup due to accretion, as mentioned above;

(5) The distribution of T_{eff} / log L / $\dot{M}$ for CV white dwarfs, versus orbital period and CV subtype, holds vital clues to the evolutionary big picture of cataclysmic evolution—the question of evolution across the period gap—the question of whether CV white dwarf masses decrease with time due to repeated classical nova explosions or increase with time —the prospect of insight into long term accretional heating, limit cycle evolution, and the nature of their ultimate evolutionary state.

But what have spectroscopic studies of their exposed photospheres taught us about accreting degenerate stars? How do they differ from the observed properties of single (field) non-explosive degenerates where gravitational and thermal diffusion (due to the enormous gravity causing heavy elements to sink and the lightest element to float at the surface), convective mixing and dredgeup, radiative levitation, and possible extremely low (interstellar) accretion, and (in the hottest objects) mass loss, appear to be operating? In single objects, accretion timescales are long relative to the diffusion times and hence there should be an exact equilibrium balance established between accretion and diffusion. For a white dwarf in a cataclysmic, ongoing accretion at a low rate, interrupted every few weeks to months by intense accretion of days to weeks (a dwarf nova accretion event), and every few thousand years by a thermonuclear explosion (the classical nova), heats the white dwarf, adds mass with processed or solar composition chemical abundances and injects angular momentum into its envelope, thus raising the question of spinup and accretion equatorial belts. Indeed, any differences would be expected to shed light on the accretion process itself.

In this talk I will focus on the progress made so far with HST spectroscopy of two of the best-studied dwarf novae, U Geminorum and VW Hydri. In doing so, one can easily see the crucial role that AAVSO observers have played in the physical parameters and breakthroughs which have emerged. The topics I will cover are: (1) CV white dwarf surface temperatures; (2) the heating and cooling of CV white dwarfs due to episodic accretion; (3) CV white dwarf rotational velocities; (4) detection of accretion belts on CV white dwarfs; (5) CV white dwarf chemical abundances; and (6) concluding remarks.

2. Surface temperatures of CV degenerates

The surface temperature of a single white dwarf directly yields its luminosity and hence its evolutionary thermal cooling time (age). For white dwarfs in CVs, however, the evolutionary interpretation of temperature and surface luminosity is complicated by instantaneous re-radiated accretional heating; by the slow, time-averaged release of gravitational potential energy due to structure changes; by angular momentum transport via shear mixing; by compressional heating; and by the release of injected thermonuclear energy associated with nova limit cycle evolution (Sion 1985). Thus the surface temperature may not be the intrinsic value independent of accretional heating, but instead an upper limit to the baseline T_{eff} value. It follows that the cooling evolution time cannot be directly inferred and is a lower limit to the stellar cooling age (Sion 1991). Note, however, if the core mass erodes with time through repeated novae, then the mass reduction would lead to adiabatic expansion and cooling, altering the cooling clock and preventing an even lower cooling age limit.

3. Measurements of white dwarf heating/cooling in response to dwarf nova accretion events

Observations of the white dwarfs in CVs offer insights into the accretion physics by determining the rate of white dwarf cooling. The characteristics of the cooling can reveal the physics of the heating mechanism (e.g., boundary layer irradiation, compressional heating, or shear mixing luminosity), the physical depth of envelope heating, as well as the geometry of accretional heating, e.g., tangential (equatorial) via a belt or radial. Moreover, the associated flux decline provides a means of reconciling observations of dwarf nova quiescence far-UV flux declines with disk instability theory, which predicts an increasing far-UV flux (i.e., an increasing accretion rate during quiescence of a dwarf nova), as well as a test of inner disk evaporation models during dwarf quiescence (Meyer and Meyer-Hofmeister 1994). Ultimately, such knowledge, applied in the long term, can reveal whether the heating over time will affect the timescale to thermonuclear runaway (TNR), since the distribution of mass, energy, and angular momentum in the accreted + white dwarf mass determines when a TNR occurs.

A UV flux decline, if due to a decrease in flux from the accretion disk during dwarf nova quiescence, would contradict the standard disk instability theory which predicts the disk should brighten through the quiescent interval because the accretion rate is gradually increasing. On the other hand, if inner disk evaporation occurs, accompanied by a hot corona and mass loss, then an associated flux decline will occur whose magnitude depends on the size of the hole in the inner disk during quiescence (La Dous, Meyer, and Meyer-Hofmeister 1997; Liu, Meyer and Meyer-Hofmeister 1995) during quiescence. Hence, this effect as well as the cooling white dwarf may both contribute to the observed flux declines (La Dous, Meyer, and

Meyer-Hofmeister 1997). However, these flux declines could be accounted for if they are due to cooling of the white dwarf in response to the accretion event. HST observations of three systems have provided conclusive evidence of white dwarf cooling in response to the accretion event.

The first such system to be studied was U Geminorum. A number of investigations demonstrated that the white dwarf in U Gem dominates the system light during quiescence in the far UV (Panek and Holm 1984; Kiplinger *et al.* 1991; Long *et al.* 1994). The work by Kiplinger *et al.* (1991) presented inconclusive evidence of white dwarf cooling using IUE. However, Long *et al.* (1994) observed U Gem in quiescence with HST/FOS at 13 days and 70 days after a normal dwarf nova outburst. They found a flux decline of 28% between the two observations and, that the white dwarf had cooled from 39,400K down to 32,100K between the two observations. The AAVSO light curve corresponding to the time of our HST FOS observations is displayed in Figure 1.

Surprisingly, when the post-outburst (POB) cooling measurements were carried out at a higher (GHRS G160M grating) resolution by Sion *et al.* (1998), a quite different degree of heating and cooling was obtained. There was an extraordinarily long quiescence experienced by U Gem in 1994/1995, which was ended after 210 days by a wide outburst in April 1995, then a short 68-day quiescence followed by the narrow outburst preceding our observations. The GHRS data are shown in Figure 2 for the observations at 13 days POB and 61 days POB. The white dwarf T_{eff} values 13 days and 61 days after outburst (32,000K and 29,000K, respectively) are cooler T_{eff} measurements at comparable times after outburst than in the Long *et al.* (1994) study. This is supported by a lower flux level of their GHRS spectra (by 4×10^{-14} ergs/cm^2/s/Å) compared with all other post-outburst temperature measurements at comparable times in quiescence (e.g., Sion *et al.* 1994; Long *et al.* 1993, 1994, 1995).

Their observations and the FOS observations of Long *et al.* 1994 were both obtained following a narrow outburst of U Geminorum. Since we expect that the amount of heating of the white dwarf and the subsequent rate of cooling should be similar following the same types of outburst, then it is clear that the white dwarf T_{eff} 13 days POB (32,000K) is considerably lower than the value (39,000K) measured 13 days after the narrow outburst of U Gem reported by Long *et al.* (1994). It is believed the T_{eff} difference is real and is almost certainly related to the cooling of the white dwarf. The normal quiescent interval of U Gem is 118 days (Szkody and Mattei 1984). Long *et al.* (1996) reported a T_{eff} of 29,000K 185 days into the long 210-day quiescence. Since that quiescence lasted another 25 days, it is even possible that some additional cooling of the white dwarf took place. Therefore, if the white dwarf had cooled down to 27–29,000K, the compressional heating calculations of Sion (1995) at a rate $\dot{M} = 10^{-8}$ M yr^{-1} for 7 days would predict a peak heating of only ~35,000K at the exact end of the outburst, and a subsequent cooling down to ~27,000K, which is not too far below the estimated T_{eff} at 185 days POB by Long *et al.* (1994). In this scenario, the long quiescence could have disrupted a normal time-averaged *equilibrium* between accretional heating of the upper envelope and cooling by radiation. The normal (average) equilibrium would be re-established only after a sufficient number of dwarf nova cycles.

4. Global rotational velocities

White dwarfs in the field are very slow rotators (Pilachowski and Milkey1984; Pilachowski 1987; Milkey and Pilachowski 1985), with $V \sin i < 60$ km/s. An even more stringent upper limit of $V \sin i < 40$ km/s has been derived for hydrogen-rich (DA) white dwarf stars (Heber, Napiwotzki, and Reid 1997). This poses problems for angular momentum transfer from core to envelope in the post-main sequence phase of mass loss in asymptotic giant branch (AGB) stars and post-AGB evolution. However for white dwarfs in CVs, the rotational velocities were unknown until the HST era. Questions such as how much angular momentum is transferred during tangential accretion, how the nova explosion affects the rotation, whether CV white dwarfs are spinning near breakup and hence would explain weak or missing boundary layer energy, and whether the entire white dwarf could be spun up, remained unanswered. The first determination of the white dwarf rotation in a CV was based on HST spectra of the dwarf nova U Geminorum when the white dwarf dominates the far-UV spectrum during quiescence. Sion *et al.* (1994) found $V \sin i = 100$ km/s, a value confirmed with further GHRS observations (see Figure 3) by Sion *et al.* (1997) for VW Hydri.

The rotational velocity of the WZ Sge white dwarf is three times faster than the VW Hyi rotational velocity (400 km s^{-1}, Sion *et al.* 1995), and an order of magnitude faster than the rotational velocity of the white dwarf in U Gem (100 km s^{-1}, Sion *et al.* 1994). Recently, Mauche (1997) assigned a narrow peak in the EUV power spectrum of SS Cygni to the rotation of the underlying white dwarf, implying a rotational velocity of 300 km/s. This range of velocities provides an amazing first glimpse at what might be anticipated for the distribution of CV white dwarf rotational velocities. WZ Sge has the shortest orbital period of the four, and U Gem, above the CV period gap, has the longest. If CV systems evolve to increasingly shorter orbital periods through angular momentum loss and start out above the gap, then one would expect that in general the fastest rotation would be found in the oldest systems, since more spinup of the accretor would have occurred due to a longer mass transfer history. While four velocities is clearly insufficient to draw any definitive conclusions, the spread of velocities does raise profound questions about the amount of angular momentum transfer during tangential accretion, the angular momentum loss via nova explosions and dwarf nova outbursts, as a function of system age. It is clear that further rotational velocities for other systems are badly needed.

Since the rotational velocity of the white dwarf during disk accretion affects the amount of dissipation in the boundary layer region, we can carry out a preliminary comparison of the boundary layer luminosity, L_{bl}, and the ratio L_{bl} / L_{disk} for well-observed systems for which we have rotational velocities. Unfortunately, a precise comparison requires accurate white dwarf masses and *quiescent* accretion rates derived from X-ray/EUV data where the boundary layer emission dominates. These two quantities are known only very approximately for most systems.

5. Accretion belts

We define an accretion belt to mean a rapidly spinning, narrow belt on the white dwarf surface itself, centered at the white dwarf equator. A given belt is constructed by taking appropriate values of log g and T_{eff} for a stellar atmosphere, rotationally broadening the synthetic spectrum to high velocity, and multiplying the fluxes by the fractional area of the belt relative to the white dwarf surface area. On theoretical grounds an accretion belt is plausibly expected to exist in tangentially accreting non-magnetic CVs (Kippenhahn and Thomas 1978). As disk matter accretes tangentially at the equator and does so every few weeks to months in a dwarf nova, an equilibrium state should be established such that the white dwarf equatorial region spins rapidly while the higher latitudes and polar regions do not. The controlling parameter for this equilibrium state is the Richardson number, which implies a gradient of differential rotation going both inward into the white dwarf and poleward along the white dwarf surface.

Several independent spectroscopic investigations of the dwarf novae VW Hydri and U Geminorum have explored the possibility of an inhomogeneous temperature distribution on the surface of an accreting white dwarf. These studies involved HST (Sion *et al.* 1997; Cheng *et al.* 1997b), IUE archival (Gaensicke and Beuermann 1996), and HUT (Long *et al.* 1996) observations during dwarf nova quiescence.

The HUT ASTRO1 and ASTRO2 spectra of U Gem in early and late quiescence, respectively, yielded a curious result (Long *et al.* 1996). The difference spectrum (ASTRO1-ASTRO2) revealed a residual energy distribution with apparent C IV absorption, resembling a hot white dwarf with T_{eff} = 50,000K. A re-analysis by Cheng *et al.* (1997b) of the FOS spectra of U Gem produced marginal evidence for a higher-temperature equatorial region and lower-temperature poles on the white dwarf based upon goodness-of-fit parameters, compared to single temperature white dwarf fits. The existence of an accretion belt on U Gem's white dwarf is not as clear (Cheng *et al.* 1997b) as in VW Hydri, as shown below.

Using HST spectra of VW Hydri in outburst and in quiescence, Huang *et al.* (1996b) and Sion *et al.* (1996) showed that pronounced continuum curvature between 1380Å and 1550Å is a spectroscopic hallmark of disk/ring/belt UV-emitting gas in Keplerian motion near the white dwarf surface. The curved continuum hump is due to the gradual merger of the velocity-broadened redward wing of Si IV with the blueward velocity-broadened wing of C IV. This curvature is still present in spectra at quiescence but considerably less pronounced. Thus, any successful composite model in quiescence must consist of a far UV flux-dominant white dwarf (replicating the broad Lyman-α wings and core, with the high gravity and moderately slow rotation preserving the narrow photospheric metals), while simultaneously providing the curved continuum signature of a Keplerian broadening component. A reasonably good model fit consisting of an accretion belt and white dwarf photosphere to the HST spectrum of the white dwarf in VW Hydri is displayed in Figure 4.

Using synthetic spectral fits to IUE archival spectra of VW Hydri during quiescence, Gaensicke and Beuermann (1996) reached a similar conclusion using an intuitive model, namely that the spectra, including the metal lines, are best represented by a composite white dwarf model with an inhomogeneous temperature distribution across the surface. The spectroscopic similarity of EK TrA to VW Hydri (Gaensicke and Beuermann 1996) suggests that it may also have an accretion belt.

In both FOS spectra of VW Hydri, the best fitting white dwarf plus accretion belt models corresponded to over-abundances of silicon (15 solar) and carbon (20 solar) in the accretion belt. Unless radiative levitation occurs in the belt region or the secondary star has peculiar abundances, we regard these over-abundances of carbon and silicon as very preliminary. At this time we have no definitive explanation or interpretation of the enhanced carbon and silicon belt abundances. With more sophisticated spectrum synthesis codes now in development, it is possible these over-abundances will not be required in our future detailed fits.

Synthetic spectral fitting results for the physical state and surface chemistry of the white dwarf and belt one day after the end of a normal outburst have provided a crucial comparison with the characteristics of the white dwarf and belt ten days after the end of a superoutburst, analyzed earlier by Sion *et al.* (1995) and Huang *et al.* (1996b). Our results reveal: (1) the white dwarf is hotter by 2,000K one day after normal outburst than the corresponding temperature ten days post-superoutburst; (2) the chemical abundances of the white dwarf atmosphere one day post-outburst (except for iron) appear elevated relative to the same elements in the white dwarf atmosphere ten days post-SOB, i.e., the white dwarf was more metal-enriched one day post-normal outburst than ten days post-SOB. It is not implausible that only one day after a normal outburst, the spectroscopic signature of the injection of freshly accreted matter is stronger than it is ten days after a superoutburst because the accreted matter has not had as much time to dilute its chemical abundance due to lateral spreading as well as downward diffusion; (3) the fractional area of the accretion belt we derive at one day post-outburst is larger than the fractional area ten days post-superoutburst, possibly due to the more recent occurrence of the outburst accretion pulse; (4) the accretion belt temperature one day post-normal outburst is cooler (by 5,000K) than the accretion belt at ten days post-SOB.

Since the white dwarf in VW Hydri sustains a rapidly spinning accretion belt during quiescence, maintaining its temperature and spin due to repeated accretion episodes every two to three weeks, a number of implications follow from the existence of the maintained accretion belt: (1) the presence of a belt up to ten days after superoutburst implies a lower limit to the viscous spindown timescale of ten days; (2) deeper heating is required than the depth of heating associated with a downward-directed boundary layer radiation field. Since the VW Hydri boundary layer luminosity is very low (indicating a low temperature or non-existent boundary layer), it is very unlikely that irradiation alone heats the belt. Instead, shear mixing or compressional heating must provide the required deep heating. Of these, shear mixing is the more efficient, i.e., same degree of heating for less mass accreted than for pure radial compression. A rough estimate of the expected heating of an equatorial surface region due to axisymmetric compression by accreting matter can be made from radial accretion calculations by assuming the amount of compressional heating scales linearly with the surface area of the accretion zone. For parameters appropriate to the superoutburst and white dwarf of VW Hydri (two week outburst duration, 0.6 $M_\odot$ white dwarf, $\dot{M} = 1 \times 10^{-8} M_\odot$ / yr, $T_{eff} = 20{,}000$K), and an assumed belt area of 10%, the model sequences of Sion (1994) predict a belt temperature approximately 10,000K hotter than the quiescent photosphere, or 30,000K. This is very close to what we derive for the belt temperature from our synthetic spectral fitting of the post-superoutburst spectrum.

5.1. Chemical abundances

Chemical abundances of metals and helium have been derived from high S/N far-UV spectra in several CVs with exposed white dwarfs. While one typically expected solar composition accreted atmospheres in CVs with normal main sequence secondaries (and one sees this in some systems), a new frontier of investigation into CVs, accretion physics, nuclear physics, and CV evolution has unexpectedly emerged. As in single white dwarfs where metallic species and their abundances reveal processes which oppose the inexorable downward diffusion of heavy elements, the white dwarfs in CVs may reveal spectroscopic features with a mix of chemical species and/or abundance ratios which cannot result from accreted matter from a normal secondary, and may indeed be compositional clues to the evolutionary past, for example, ancient relics of the white dwarf's thermonuclear history. The situation is analogous to the triple-α-processed chemical species (C and O transitions) which linked the PG1159 degenerates as the evolutionary progeny of the Wolf-Rayet O VI planetary nuclei (Sion, Liebert, and Starrfield 1985). Two dwarf nova VW Hydri and U Geminorum well-studied during quiescence illustrate how the chemical abundances and mix of ions in the white dwarf atmosphere yield critical evolutionary clues.

In VW Hyi, Sion *et al.* (1997) determined a nitrogen abundance much greater than carbon and oxygen, and detected the odd-numbered nuclear products of proton capture nucleosynthesis (see Figure 5)! Both of these observations indicate a that prehistorical nova outburst occurred on the white dwarf in VW Hydri, the first such TNR established for a normal dwarf nova. The implications for nuclear physics are extremely important, since both the cross-sections and reaction rates of proton captures on elements heavier than those involved in the CNO bi-cycle are poorly known. Thus the abundances of proton capture elements on a white dwarf presents a fundamental test of nuclear physics. At present, the proton capture cross-sections and rates must be extrapolated from quantum mechanical calculations for light elements; the uncertainties are very large, and laboratory studies are not possible. The very presence of these greatly elevated abundances of phosphorus and aluminum in the photosphere as the products of proton captures during the hot CNO thermonuclear runaway is greatly in excess of what theory predicts. Moreover, diffusion (gravitational settling) theory for a hydrogen-rich atmosphere at 22,000K (the T_{eff} of VW Hydri) predicts a diffusion timescale of three to four days! Since we know of no TNR on VW Hydri in historic times, it seems likely that dredgeup due to shear mixing associated with an accretion belt on the white dwarf (see above), is responsible for the phosphorus and aluminum being in the photosphere.

In U Geminorum, Sion *et al.* (1998) carried out further abundance analyses of HST GHRS spectra during quiescence following two different outbursts. These abundances, together with the abundances re-determined from the FOS spectra of Long *et al.* (1994) by Cheng *et al.* (1997a), provided a higher quality, more complete abundance picture of the white dwarf's accreted atmosphere. Specifically, the carbon abundance is definitely sub-solar. If the white dwarf accretes solar or nearly solar carbon, then carbon must rapidly gravitationally settle out of its atmosphere. However, this leads to two major conflicts. First, other metals should also diffuse downward out of the atmosphere and this is not indicated by the abundances. Second, the carbon abundance has the same sub-solar value at thirteen and sixty-one days after the dwarf nova outburst. For example, ongoing accretion of a solar mix of gas during quiescence would quickly replenish diffusion-depleted carbon. Sion *et al.* (1998) propose another possible solution: an ancient thermonuclear runaway (TNR). It is fully expected that U Gem and all other dwarf novae will undergo (and have undergone in the past) a TNR when the white dwarf has accumulated sufficient hydrogen-rich material (Starrfield, Sparks, and Shaviv 1988). During a TNR, carbon proton-captures to form nitrogen. If the carbon abundance is larger than solar, then a strong TNR results, leading to a nova outburst (Starrfield 1995). This carbon overabundance comes from the accreted material mixing with the white dwarf's core material (Starrfield *et al.* 1972). Thus, most observations of novae end up with an overabundance of carbon, even though much of the carbon has been processed to nitrogen. If there is no mixing with the core, then in most cases the TNR will be weak. The notable exception is a rapidly accreting, very high mass white dwarf (~1.35 M), which is associated with recurrent novae (Sparks *et al.* 1990). For a more slowly accreting white dwarf (as in the case of a dwarf nova or a less massive white dwarf), the TNR will be weaker, little or no material will be ejected during the outburst, and a large common envelope will form. Although some of the common envelope may be ejected, a fraction will be deposited on the secondary and a similar fraction will be consumed by the white dwarf's rekindled hydrogen shell source. This shell source will leave a helium-rich material layer enriched in nitrogen and depleted in carbon. This helium layer should prevent core material from being mixed up, thus leading to subsequent weak TNRs. Later dwarf novae will deposit carbon-depleted material due to the TNR and common envelope, to be mixed with even stronger carbon-depleted white dwarf material due to the TNR and the remnant hydrogen shell burning source. Thus carbon will be depleted and the nitrogen will be enhanced in both the accreted material and the white dwarf's surface material. We did not cover any photospheric nitrogen lines in our GHRS setting with which to obtain a nitrogen abundance, but our prediction is that nitrogen should be overabundant in U Gem.

A number of our HST observations of U Gem support, or are at least consistent with, this scenario. First, the very slow white dwarf's rotation velocity and very low carbon abundance are indicators that not much material has been accreted since the last TNR. Both the carbon abundance and the rotational velocity will increase with the amount of accreted material. Second, the large white dwarf mass means that the amount of accreted mass needed to trigger TNR will be small. The small accreted mass implies that the accretion timescale will also be short. A short accretion timescale works against two of the four proposed mixing mechanisms: accretion-driven shear mixing and diffusion (Shore, Livio, and van den Heuvel 1993). The weaker TNR from the low initial carbon abundance hinders the other two mechanisms (convection-driven shear mixing and undershooting) from penetrating the remnant helium layer. If this scenario is correct, it means that U Gem and probably other dwarf novae are massive white dwarfs increasing in mass with the possibility of becoming a supernova of Type Ia (SNI).

Our discovery must be followed by a search for accretion belts in a dozen other systems with exposed white dwarfs. These further systems present a golden opportunity to deepen our insights into accretion physics, nuclear reactions, and CV long-term evolution.

6. Concluding remarks

There is no question that a substantial leap forward has been made in understanding CV evolution and accretion physics by spectroscopically analyzing the underlying exposed white dwarfs in CVs. However, given the present fragmentary state of knowledge, earmarked by individual analyses of a few very different systems and large uncertainties in fundamental parameters, physical implications and definitive interpretations cannot be made. For example, cooling curves and physical heating mechanisms of accretion-heated white dwarfs cannot be definitively interpreted unless white dwarf masses and accretion rates are pinned down with sufficient accuracy. Hence, we are still in the realm of speculation in many of the topics covered here. We must advance to a more global picture of CV evolution and accretion physics by enlarging the observable sample. This requires a commitment on the part of observatory and mission directors to ensure that sufficient observing time is allocated to accelerate the accumulation of CV white dwarf properties beyond the present slow pace of one to two systems at a time. Only then will the wealth of information contained in CV white dwarfs be attainable. These white dwarfs can greatly aid in our quest to understand the evolution of CVs from their common envelope origin to their extinction as mass-transferring binaries.

7. Acknowledgements

Our ongoing close cooperation with the AAVSO is most gratefully acknowledged. A special thanks is extended to Director Janet Mattei, Danie Overbeek, Frank Bateson, Albert Jones, and an entire host of AAVSO observers, without whom we could not have achieved our HST scientific objectives. I thank the SOC for their kind invitation to speak at the Spring meeting in Sion. I am deeply grateful for the expertise, energy, and enthusiasm of my close collaborators on HST projects: Paula Szkody, Fu-hua Cheng, Warren Sparks, Min Haung, and Ivan Hubeny. This work is supported by NASA grants GO-3836.01-91A, GO5412.01-94A, and GO-6084.01-95A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA Contract NAS5-26555, and by NASA LTSA grant NAGW-3726.

8. Addendum, 2006

This addendum provides a brief update of topics in the foregoing paper since the time of the AAVSO conference in Sion, Switzerland.

The two-temperature white dwarf fits to FUV data are an attempt to explain the nature of an unidentified second component of FUV flux which is present in many dwarf novae during their quiescent intervals between outbursts. The explanation for the second components present in the quiescent spectra of both U Gem and VW Hydri as accretion belts, first theorized to exist by Kippenhahn and Thomas (1978), has since been questioned on two grounds: (1) there are no detected line features which characterize the presence of such a belt and; (2) the results of semi-analytic calculations of spreading layers in accreting white dwarfs (Piro and Bildsten 2004) suggest that during quiescence, the accretion rate is so low that any accretion belt would lie at a latitude too low for spectroscopic detection and that, in any case, the spin down timescale of such a belt is very short. Piro and Bildsten (2004) predict that the spin down of such a belt would occur very shortly after the outburst ends. The nature of the FUV flux component present in the IUE, FUSE, and HST FUV spectra of dwarf novae in quiescence remains unresolved. Candidates besides a rapidly spinning accretion belt sustained during the quiescence of dwarf novae include a rapidly spinning optically thick ring in the boundary layer region just above the white dwarf surface, the inner accretion disk itself, or disk continuum from irradiation of the upper disk by the hot white dwarf. The X-ray study by Belloni *et al.* (1991) suggesting a weak or missing boundary layer in VW Hydri has also been challenged. Recent XMM-Newton X-ray observations by Pandel *et al.* (2003) find that in nine dwarf novae during quiescence, there is no deficiency of boundary layer luminosity relative to the accretion disk luminosity. In other words, these observations suggest there is no longer a so-called "missing boundary layer."

The compositions of the accreting white dwarfs in U Gem and VW Hydri are essentially correct as they were reported. The surface abundances of the white dwarfs reported at the Sion meeting for VW Hyi and U Gem have been confirmed by numerous independent spectroscopic studies using FUSE and HST spectra. The elevated phosphorus abundance has been found (albeit at much lower abundance) in other SU UMa-type dwarf novae like VW Hyi. The elevated nitrogen/carbon surface abundance ratio reported for the photospheres of the white dwarfs in U Gem and VW Hyi has been confirmed but high N/C photospheric abundance ratios have not as yet been established in the surface layers of other white dwarfs in CVs.

The rotation rates reported at the Sion meeting have also been confirmed for VW Hyi and U Gem by other spectroscopic studies with both FUSE and HST. However, the rotation rate of the white dwarf in WZ Sge remains controversial, in part because it remains unclear whether the absorption lines from which it was determined originate in the photopshere. Moreover, the rotational velocities derived from absorption line fitting are affected by the chemical abundances for those same lines. The rotation rates of white dwarfs in CVs, while very rapid relative to the rotation of single field degenerates, are all below 20% Keplerian and hence rotating much more slowly than simple spin up due to angular momentum transfer during long term accretion would predict (Livio and Pringle 1998). The surface temperatures reported for the white dwarfs in U Gem and VW Hyi are solidly confirmed by numerous other authors. VW Hyi's white dwarf is among the hottest known in systems below the period gap, while the white dwarf in U Gem is among the coolest known in systems above the period gap.

References

Belloni, T., *et al.* 1991, *Astron. Astrophys.*, **246**, L44.

Cheng, F. H., Sion, E. M., Horne, K., Hubeny, I., Huang, M., and Vrtilek, S. D. 1997a, *Astron. J.*, **114**, 1165.

Cheng, F. H., Sion, E. M., Szkody, P., and Huang, M. 1997b, *Astrophys. J., Lett.*, **484**, L149.

Cordova, F. 1995, in *X-Ray Binaries*, eds. W. H. G. Lewin, J. van Paradijs, E. P. J. van den Heuvel, Cambridge Univ. P., Cambridge, 331.

Gaensicke, B. T., and Beuermann, K. 1996, *Astron. Astrophys.*, **309**, L47.

Heber, U., Napiwotzki, R., and Reid, N. 1997, *Astron. Astrophys.*, **323**, 819.

Huang, M., Sion, E. M., Hubeny, I., Cheng, F., and Szkody, P. 1996a, *Astrophys. J.*, **458**, 355.

Huang, M., Sion, E. M., Hubeny, I., Cheng, F., and Szkody, P. 1996b, *Astron. J.*, **111**, 2386.

Kiplinger, A. L., Sion, E.M., and Szkody, P. 1991, *Astrophys. J.*, **366**, 569.

Kippenhahn, R., and Thomas, H.-C. 1978, *Astron. Astrophys.*, **63**, 265.

La Dous, C., Meyer, F., Meyer-Hofmeister, E. 1997, *Astron. Astrophys.*, **321**, 213.

Liu, F. K., Meyer, F., and Meyer-Hofmeister, E. 1995, *Astron. Astrophys.*, **300**, 823.

Livio, M., and Pringle, J. 1998, *Astrophys. J.*, **505**, 339.

Long, K. S., Blair, W. P., Bowers, C. W., Davidsen, A. F., Kriss, G. A., Sion, E. M., and Hubeny, I. 1993, *Astrophys. J.*, **405**, 327.

Long, K. S., Blair, W. P., and Raymond, J. C. 1995, *Astrophys. J., Lett.*, **454**, L39.

Long, K. S., Mauche, C. W., Raymond, J. C., Szkody, P., and Mattei, J. A. 1996, *Astrophys. J.*, **469**, 841.

Long, K. S., Sion, E. M., Szkody, P., and Huang, M. 1994, *Astrophys. J., Lett.*, **424**, L49.

Mauche, C. W. 1997, *Astrophys. J., Lett.*, **476**, 85.

Mateo, M., and Szkody, P. 1984, *Astron. J.*, **89**, 863.

Meyer, F., and Meyer-Hofmeister, E. 1994, *Astron. Astrophys.*, **288**, 175.

Milkey, R. W., and Pilachowski, C. A. 1985, *Publ. Astron. Soc. Pacific*, **97**, 634.

Pandel, D., Cordova, F. A., and Howell, S. B. 2003, *Mon. Not. Roy. Ast. Soc.*, **346**, 1231.

Panek, R., and Holm, A. V. 1984, *Astrophys. J.*, **277**, 700.

Pilachowski, C. A. 1987, *Publ. Astron. Soc. Pacific*, **99**, 836.

Pilachowski, C. A., and Milkey, R. W. 1984, *Publ. Astron. Soc. Pacific*, **96**, 821.

Piro, A. L., and Bildsten, L. 2004, *Astrophys. J.*, **610**, 977.

Shafter, A. W., Robinson, E. L., Crampton, D., Warner B., and Prestage, R. M. 1985, *Astrophys. J.*, **354**, 708.

Shore, S., Livio, M., and van den Heuvel, E. P. J. 1993, in *Lecture Notes of the 22nd Advanced Course of the Swiss Society for Astronomy and Astrophysics (SSAA)*, eds. H. Nussbaumer, A. Orr, Springer, Berlin.

Sion, E. M. 1985, *Astrophys. J.*, **297**, 538.

Sion, E. M. 1991, *Astron. J.*, **102**, 295.

Sion, E. M. 1995, *Astrophys. J.*, **438**, 876.

Sion, E. M., Cheng, F-H., Huang, M., Hubeny, I., and Szkody, P. 1996, *Astrophys. J., Lett.*, **471**, L41.

Sion, E. M., Cheng, F. H., Sparks, W. M., Szkody, P., Huang, M., and Hubeny, I. 1997, *Astrophys. J., Lett.*, **480**, L17.

Sion, E. M., Cheng, F. H., Szkody, P., Sparks, W. M., Gaensicke, B., Huang, M., and Mattei, J. A. 1998, *Astrophys. J.*, **496**, 449.

Sion, E. M., Liebert, J., and Starrfield, S. G. 1985, *Astrophys. J.*, **292**, 477.

Sion, E. M., Long, K. S., Szkody, P., and Huang, M. 1994, *Astrophys. J., Lett.*, **430**, L53.

Sion, E. M., Szkody, P., Cheng, F. H., and Huang, M. 1995, *Astrophys. J., Lett.*, **444**, L97.

Sparks, W. M., Kutter, G. S., Starrfield, S., and Truran, J. W. 1990, in *The Physics of Classical Novae*, eds. A. Cassatella, R. Viotti, Springer, Berlin, 361.

Starrfield, S. G. 1995, in *Physical Processes in Astrophysics*, ed. I. Roxborough, Springer, Berlin, 99.

Starrfield, S. G., Sparks, W. M., and Shaviv, G. 1988, *Astrophys. J., Lett.*, **325**, L35.

Starrfield, S. G., Truran, J. W., Sparks, W. M., and Kutter, G. S. 1972, *Astrophys. J.,* **176**, 169.

Szkody, P., and Mattei, J. A. 1984, *Publ. Astron. Soc. Pacific*, **96**, 988.

Warner, B. 1995, *Cataclysmic Variable Stars*, Cambridge Univ. P., Cambridge.

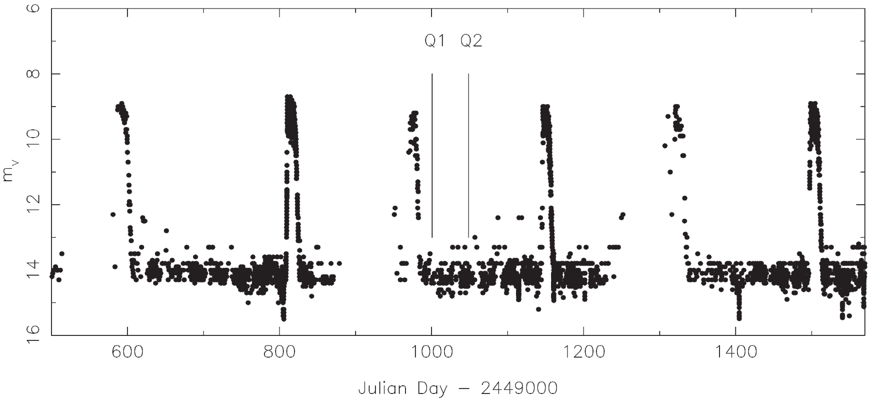

Figure 1. The AAVSO light curve showing U Gem at quiescence, corresponding to the time of our HST FOS observations.

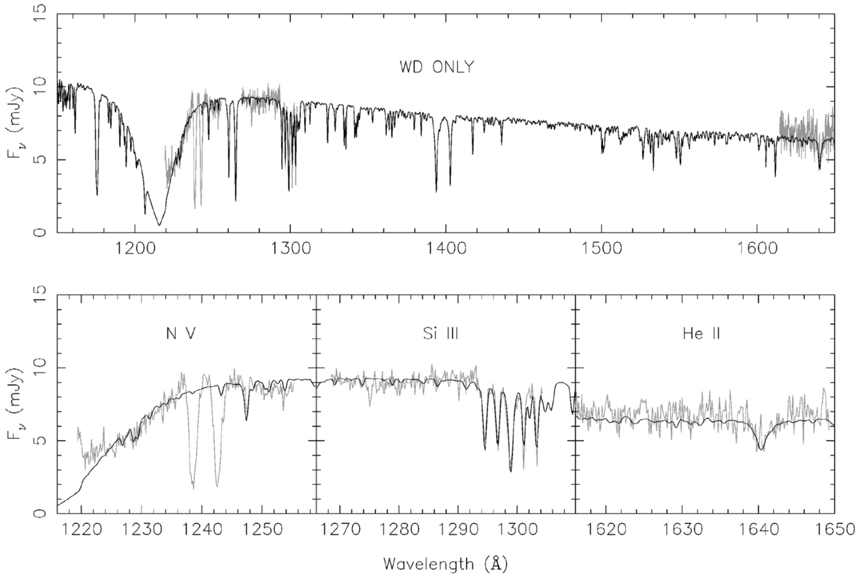

Figure 2. The best rotating white dwarf model fit to the three combined GHRS wavelength regions at thirteen days post-outburst (top panel). The model fluxes are shown in bold face and span the wavelength range 1150 Å to 1650 Å while the limited range of the three GHRS spectra are shown with a lighter shade. The individual GHRS G160M regions for N V, Si III, and He II are shown in the bottom panels. Note that the observed N V features cannot be accounted for by the white dwarf fluxes. Note also the photospheric C III λ1247 absorption feature just longward of N V λ1242. The best-fitting rotational velocity is *V sin i* = 100 km/s.

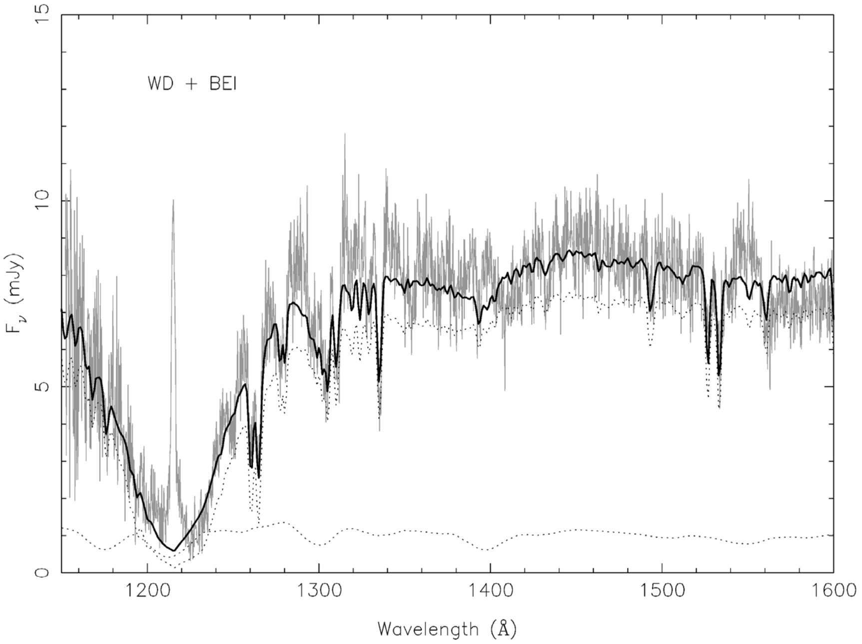

Figure 3. The FOS spectrum of VW Hydri obtained 10 days after superoutburst. The best-fit parameters differ slightly from Sion *et al.* 1995, due to our inclusion of the H_2 quasi-molecular satellite absorption features and a rotational broadening of 300 km/s.

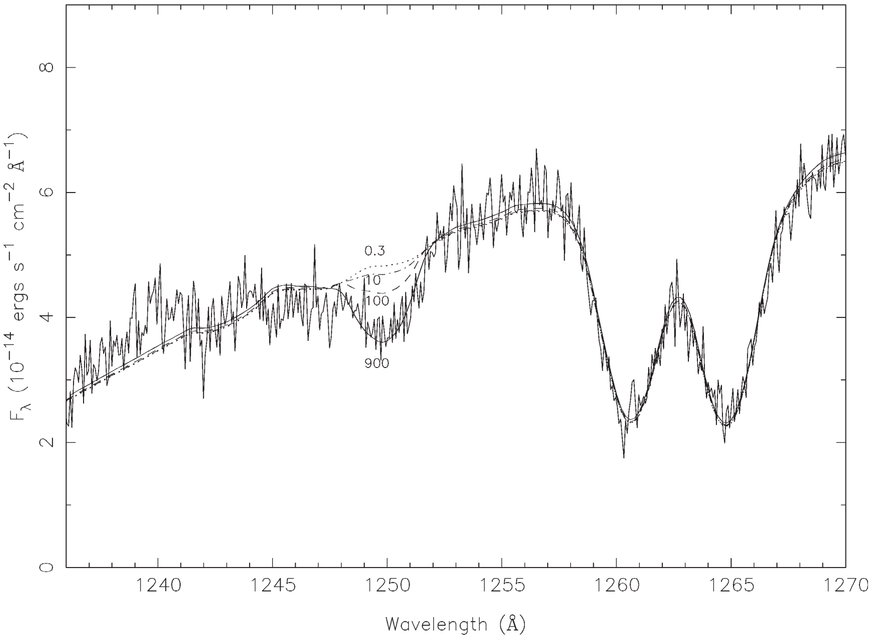

Figure 4. The flux (F_λ) versus wavelength (Å) G160 spectrum of the Si II λλ1260, 1264 region in VW Hydri, revealing the strong photospheric components of Si II and the broad deep absorption due to a blend of P II lines. Superimposed on the HST spectrum are four synthetic spectra corresponding to four values of the phosphorus abundance and T_{eff} = 22,000 K, log g = 8.43, V_{rot} = 400 km s^{-1}. The dotted fit is for P of 0.3 solar, the dashed-dot fit for 10 solar, the dashed fit for 100 solar, and the solid for 900 solar.