# THE HOPKINS ULTRAVIOLET TELESCOPE OBSERVATIONS OF DWARF NOVAE

**Knox S. Long**
Space Telescope Science Institute
3700 San Martin Drive
Baltimore, MD 21218

Dept. of Physics and Astronomy
Johns Hopkins University
Baltimore, MD 21218

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## Abstract

Due in part to a productive interaction between amateur and professional astronomers, rapid progress has been made in recent years in understanding the far ultraviolet spectra of dwarf novae. We now know that the disk, a wind emerging from the inner portions of the system, the bright spot, and the white dwarf all contribute to the observed spectra. In this paper, I provide a brief overview of our current understanding of dwarf novae and of the continuing challenges they present in the context of the observations of dwarf novae made with the Hopkins Ultraviolet Telescope on the Astro-1 and Astro-2 space shuttle missions. These observations are significant because they provide the first set of moderate (3Å) resolution far ultraviolet spectra of dwarf novae to include the wavelength range between Lyman $\alpha$ (1216Å) and the Lyman limit (912Å).

## 1. Introduction

Dwarf novae (DNe) are binary star systems, consisting of a white dwarf (WD) star and a relatively normal late-type companion orbiting one another, with periods ranging from about 1 hour to 1 day. The separation between the two stars in the system is on the order of $10^{11}$ cm, or about the size of the sun. The orbital separation between the WD and the secondary star decreases (very slowly) with time and, as a result, matter spills from the secondary star onto the more massive (but much smaller diameter) WD. In DNe, the matter spilling through the inner Lagrangian point between the two stars forms a disk around the WD star. Viscous forces (essentially friction) between adjacent rings of material in the disk cause material to move through the disk and allow some, probably most, of this material to accrete onto the surface of the WD. Binary star systems of this type are called DNe because they undergo quasiperiodic outbursts of 3–5 magnitudes at optical wavelengths. Depending on the object, the interval between outbursts can be as short as a few weeks or as long a few tens of years. The outburst itself is due to a change in the physical state of the accretion disk. Some of the brightest DNe, including SS Cyg and U Gem, have been observed by amateur astronomers of the AAVSO for more than a century (Cannizzo and Mattei 1992).

DNe are subset of a group of closely related objects known as cataclysmic variables (CVs). All CVs are WD-normal star binaries with short orbital periods which exchange mass. However, in some other subgroups the WD has a strong magnetic field that disrupts all, or at least the inner part, of the accretion disk and channels the material down to the foot-points of the magnetic field, much as the earth's far weaker magnetic field channels particles down into our atmosphere to form the Aurora Borealis (see, e.g., Cropper 1990; Warner 1983). While magnetic CVs do not undergo the dramatic outbursts seen in DNe, they do exhibit irregular short (minute-to-minute) and long (month-to-month) variability, associated with the transit of material down the accretion column and long term changes in the accretion rate. They also show periodic behavior associated with the orbital period of the system or the rotation period of the magnetic WD.

CVs are important objects to study for a variety of reasons. They are excellent laboratories for studying the physics of accretion disks and of magnetic flows, in part because the WD and normal star that make up the binary are relatively well understood. Accretion disks are one of the most common of astrophysical structures. They are needed to form stars and planetary systems and to power quasars. The physics of magnetic CVs are similar to the physics needed to understand pulsating X-ray binaries, which contain rapidly rotating neutron stars with even stronger magnetic fields than CVs. In addition, CVs represent one track in the evolution of low-mass binary stars. It is certain that some of the systems we see today as CVs are also the objects which produce novae, as a result of explosive nuclear burning of material which has been collected from the normal companion (see, e.g., Shara 1989). It is also possible that CVs are the progenitors of Type Ia supernovae.

In this paper, however, we will limit ourselves to a discussion of DNe. As shown in Figure 1, there are a number of potential emitting regions in a DN system. These include the normal star, the stream between the normal star and the disk, the "bright spot" produced by the interaction of the stream and the disk, the disk itself, the "boundary layer" between the accretion disk and the WD, and the WD. These emitting regions contribute different portions of the light at various wavelengths and in outburst and quiescence. The amount of gravitational energy L released as a result of the transfer of material from the normal star to the WD is equal to $GM\dot{m}/r$, where G is the gravitational constant, M is the mass of the WD, $\dot{m}$ is the mass accretion rate, and r is the radius of the WD. In the standard theory of accretion disk systems as applied to CVs, half of this luminosity is radiated as the material traverses the accretion disk itself, and the remainder is radiated by the boundary layer (see, e.g., Lynden-Bell and Pringle 1974). The outbursts of DNe are understood to arise from a change in the state of the accretion disk which produces a change in the accretion rate $\dot{m}$. In outburst, in the standard theory, the disk is optically thick and hot, and the disk dominates both the optical and far ultraviolet (FUV) light from the DN. In quiescence, the disk is optically thin and cool (~5,000 K; Cannizzo, Ghosh, and Wheeler 1982), and other portions of the system may dominate. In particular, observations show that the "bright spot" can compete with the disk at optical and near-UV wavelengths, and the WD is expected to be prominent in the FUV. In the most commonly accepted theory (Osaki 1974; Meyer and Meyer-Hofmeister 1981), the outburst itself results from the fact that in quiescence material is being added to the outer edge of the disk more rapidly than it exits at the inner edge. In quiescence, most of the hydrogen in the disk is in the form of a neutral atomic gas. However, as the disk mass grows, the temperature of the disk increases until, at some point, hydrogen begins to ionize to free electrons and protons. This triggers an instability that converts the disk from a cool, low mass transfer state to a hot, high transfer state. The outburst process is a bit like spontaneous combustion. Once the "wood" in the disk has been lit, it will burn until a large fraction of the "wood" has been exhausted. In actuality, what this means is that during the outburst, more material is dumped from the disk than is being transferred from the secondary star, reducing the mass of the disk to a point at which the outburst can no longer be sustained.

Although DNe are spectacular objects at optical wavelengths, they emit a much larger fraction of their energy in the FUV. As a result, the launch in 1978 of the International Ultraviolet Explorer, the first satellite with sufficient sensitivity in the FUV to observe DNe, triggered a great deal of interest and progress in understanding

Figure 1. A conceptual view of a DN. Matter is funneled from the normal star whose surface is distorted by gravity through the inner Lagrange point into an accretion disk surrounding the WD star. In addition to the disk and the WD, emission can arise in the interaction region, known as the "bright spot," where the incoming gas stream encounters the disk, and the "boundary layer" region between the inner accretion disk and the WD.

DNe. In fact, IUE has been used to obtain more than 1000 spectra of about 50 DNe, covering the wavelength range 1160–3000Å, with a resolution of ~ 6Å (La Dous 1990). Using these spectra, IUE observers have been able to show that the spectra of DNe in outburst do resemble those expected from an optically thick disk, that a wind appears to be emerging from the inner portion of the system, that the UV outburst is often delayed with respect to the optical outburst, and that the quiescent spectra of a few DNe do indeed resemble a WD. The results obtained with IUE have been the subject of numerous conferences and reviews (e.g., Córdova 1995).

In this paper, however, I would like to describe observations made with a different instrument, the Hopkins Ultraviolet Telescope. This instrument, which was designed to fly on the space shuttle, can be used to obtain FUV (840–1840Å) spectra of a wide range of astrophysical objects with a resolution of 3Å. HUT differs from most other FUV telescopes, including the International Ultraviolet Explorer and the Hubble Space Telescope, because HUT is optimized for the wavelength range between Lyman α and

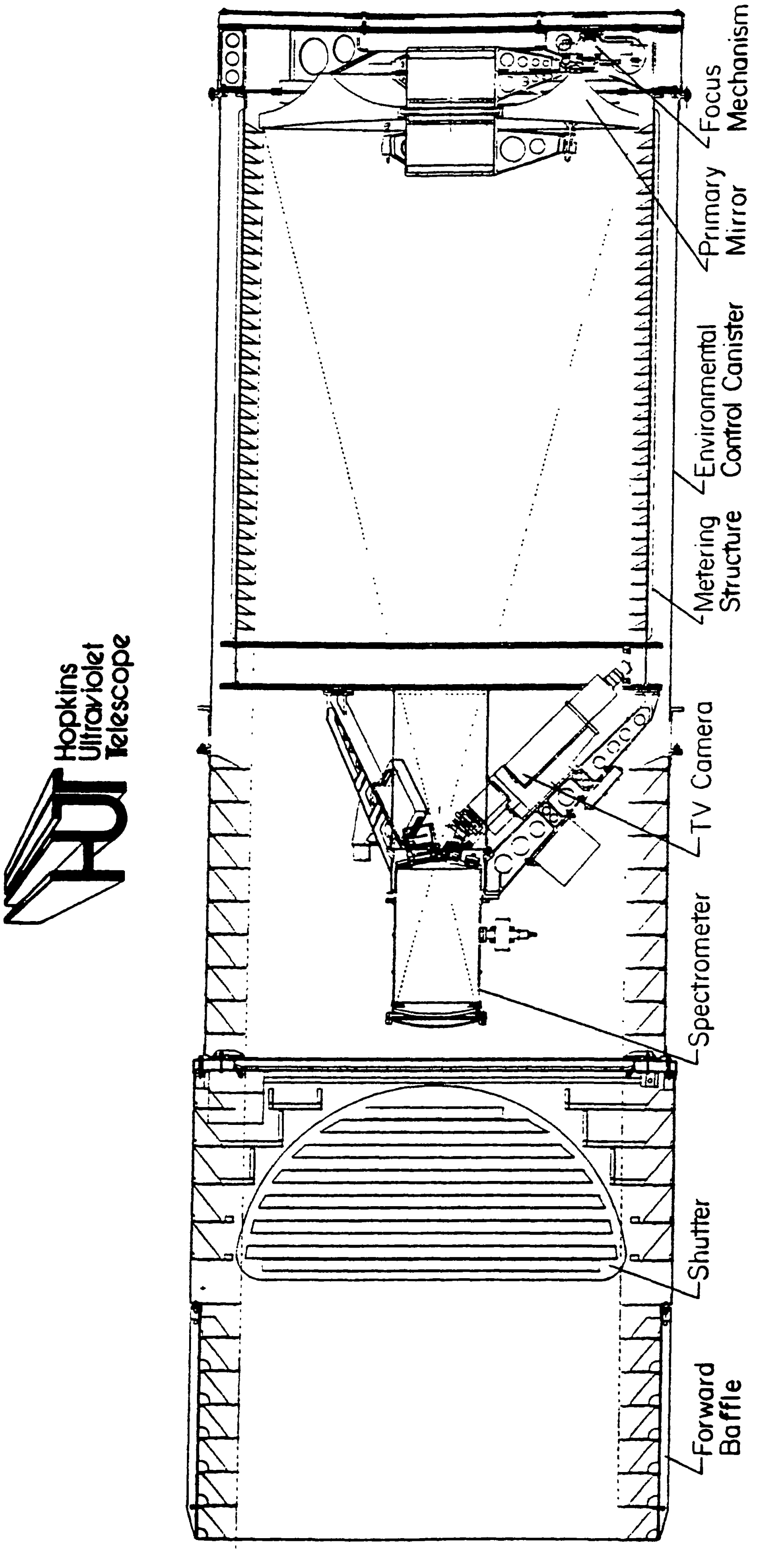

Figure 2. The Hopkins Ultraviolet Telescope. The overall length of the telescope and baffling structure is 3.8 m. Light enters the telescope from the left, reflects off the primary mirror, passes through a selectable set of apertures at the prime focus, and is diffracted into the detector by a grating located at the back (left) end of the spectrograph. Although some of the detector electronics are mounted inside the telescope, most of the experiment electronics, including the HUT computers, are located in a separate module.

the Lyman limit at 912Å. (Between the Lyman limit and about 100Å, the galaxy is mostly opaque due to absorption from neutral hydrogen in the interstellar medium). The wavelength region between Lyman-$\alpha$ and the Lyman limit is particularly important because it contains the higher order Lyman lines of hydrogen and a number of strong transitions of highly ionized atoms, including O VI $\lambda\lambda$1032, 1038, which can be used to constrain models of DNe (and other less interesting objects).

## 2. The HUT instrument and the observations of dwarf novae

As shown in Figure 2, HUT consists of a 0.9-m f/2 primary mirror which feeds a prime focus spectrograph with a photon-counting microchannel plate detector. The design of the telescope and spectrograph is relatively simple, involving only two reflections, because the reflectivity at 1000Å of the "best" materials is only 30–40%. HUT has been flown twice on the space shuttle, first in December 1990 on Astro-l, and more recently in March 1995 on Astro-2. In orbit, HUT is operated much like a ground-based telescope. Mounted on the shuttle's Instrument Pointing System along with two other telescopes, the Wisconsin Ultraviolet Photopolarimetry Experiment and the Ultraviolet Imaging Telescope, the shuttle crew pointed HUT toward an astronomical target. HUT has a finder camera which views the HUT focal plane. Fine pointing was carried out by one of the payload specialists, who identified the target from specially prepared star charts and moved the target into the aperture (with coaching from those of us who were watching anxiously from the ground). HUT and its performance on Astro-1 and Astro-2 have been described in more detail by Davidsen *et al.* (1992) and Kruk *et al.* (1995).

HUT was used to observe a wide range of solar system, galactic, and extragalactic objects on both Astro-1 and Astro-2 (see, e.g., Davidsen 1993 and the Nov. 20, 1995 issue of *Astrophys. J., Lett.*). In 1990, when the Astro-1 mission took place, the only observations of DNe in the 900–1200Å spectral range had been made with UV spectrometers aboard the Voyager probes. Designed primarily to observe Jupiter, the Voyager UV spectrometers had very modest spectral resolution (15Å) compared to HUT (3Å) and were far less sensitive than HUT. Consequently, Voyager was able to detect only a few DNe in outburst and none in quiescence (Polidan, Mauche, and Wade 1990). The primary goal of our DNe program on Astro-1 was therefore to obtain high S/N spectra of DNe in outburst and in quiescence, which could be compared with model predictions for the spectra of disks and of WDs. We succeeded in observing 3 DNe on Astro-1: Z Cam at the peak of a normal outburst, and SS Cyg and U Gem in quiescence. In addition, we observed two novalike variables, UX UMa and IX Vel. (Novalike variables are nonmagnetic CVs that appear to be "stuck" in the outburst state.) By the time of Astro-2, our goals had expanded. We wanted to observe a number of quiescent systems, because, as will be discussed below, although the quiescent spectrum of U Gem appeared to be dominated by the WD, the quiescent spectrum of SS Cyg did not. And now, no longer content to obtain a single snapshot of a system in outburst, we wanted to observe at least one system multiple times as it evolved through an outburst. These goals were largely achieved. On Astro-2, we observed seven DNe: YZ Cnc, SS Cyg, U Gem, VW Hyi, and WX Hyi in quiescence, and Z Cam and EM Cyg in outburst. Most of the DNe were observed more than once.

During Astro-1 and especially during Astro-2, we worked closely with Janet Mattei and the observers of the AAVSO to predict the outburst status of potential targets on a daily basis. Due to appeals which the AAVSO had made to observers around the world, up-to-date summaries of the visible light curves of about 20 potential targets were sent to members of the HUT team in the Payload Operations Control Center at NASA's Marshall Space Flight Center. This information was used to select targets for observation. After a target had been selected, the observation had to be coordinated with the other

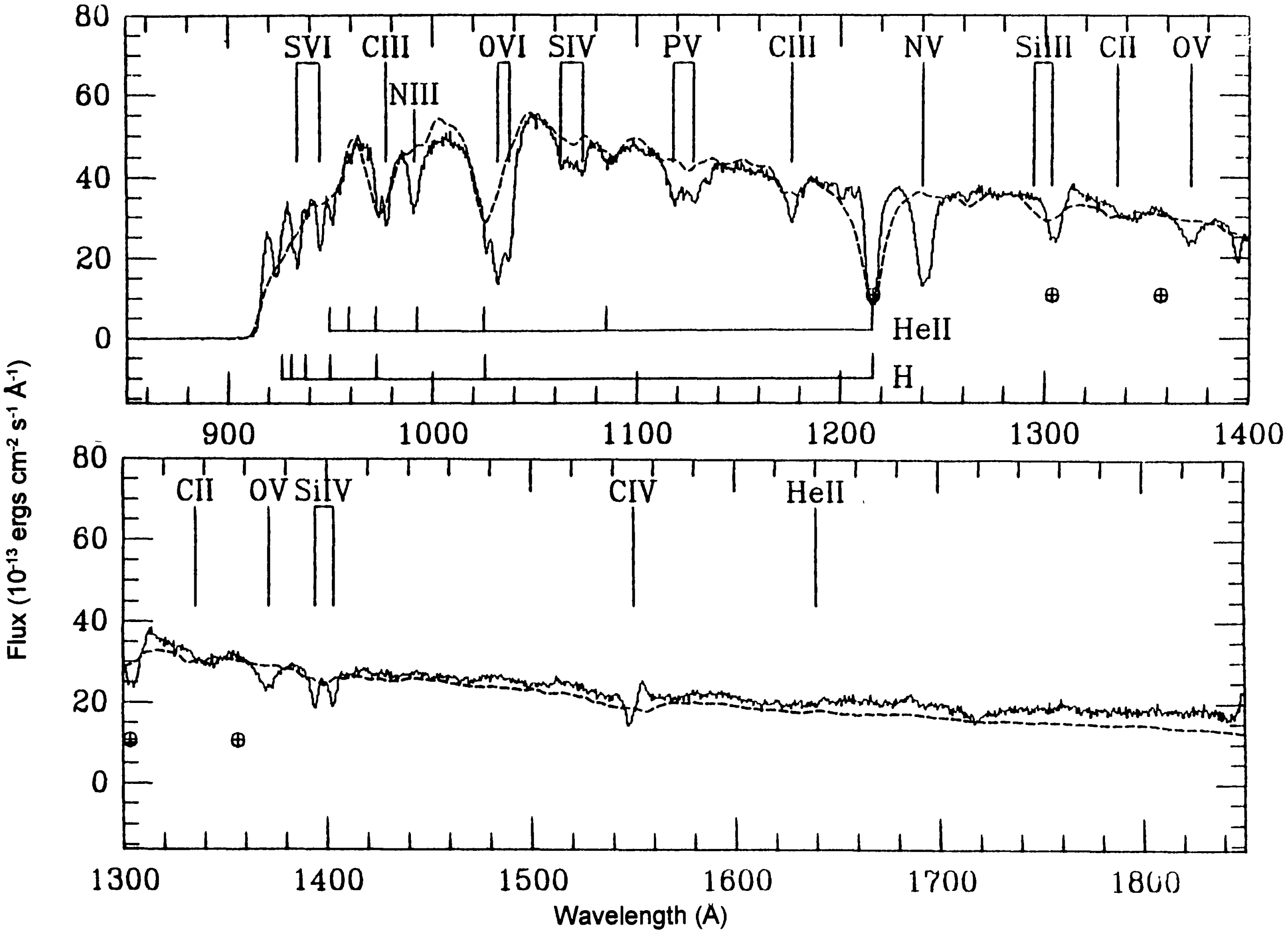

Figure 3. Z Cam as observed with HUT on Astro-2 in 1995 March near the peak of an optical outburst. The spectrum has numerous broad absorption features, such as O VI λλ1032, 1038, N V λλ1239, 1243, and C IV λλ1548, 1551, which are due to the wind emanating from the accretion disk and/or the WD. The dashed curve is a model for a steady state accretion disk with $\dot{m}$ of 4 x $10^{17}$ g $s^{-1}$ at an assumed distance of 200 pc. The model reproduces the overall spectral shape and flux fairly well, but does not account for the broad absorption lines (and should not be expected to do so). Regions of the spectra affected by airglow are indicated by the ⊕ symbols.

instrument teams, detailed maneuvers and orientations of the orbiter and the pointing system had to be planned, instrument setups had to be reviewed and transmitted to onboard computers, and procedures for the crew had to be reviewed and discussed with the crew before the observation could take place. Even though the resulting planning cycle was about a day, this is considerably shorter than the length of the outbursts of many DNe, such as EM Cyg, which we observed three times from the peak through the declining phase of the outburst, and Z Cam, which we were able to observe in outburst simultaneously with the ASCA X-ray satellite.

## 3. Observations of dwarf novae in outburst

In the "high" state, an optically thick accretion disk dominates the spectrum of DNe in the FUV. The spectrum obtained of Z Cam on Astro-2, shown in Figure 3, is typical. The continuum spectrum is fairly "blue" (brighter toward shorter wavelengths) and has an effective color temperature on the order of 30,000 K. The continuum can be modeled in terms of an appropriately weighted sum of stellar spectra, given the run of temperature and surface gravities predicted for a steady-state accretion disk (see, e.g., Wade 1988; Long *et al.* 1991). Z Cam is thought to lie a distance of 200 pc, and have an inclination angle of about 57 degrees, a WD mass of about 0.7 $M_\odot$, and a reddening E(B-V) of about 0.02. The model shown in Figure 3 assumes these parameters and a mass accretion rate of $4 \times 10^{17}$ g $s^{-1}$.

The continuum is punctuated by broad absorption lines that can be identified as resonance transition lines of ions in an ionized plasma. The model does not account for most of these lines. Many of the lines, especially O VI λλ1032, 1038, N V λλ1239, 1243, and C IV λλ1548, 1551, require much higher temperatures than the disk model predicts, and, more important, the hot inner disk is rotating so rapidly that the lines produced there would be washed out by Doppler broadening. The effect of Doppler broadening can be seen in the Si IV λλ1394, 1403 region of the spectrum. The broad dip in the model spectrum is due to Si IV λλ1394, 1403, but the doublet nature of this line is smeared out by rotation. Most of the lines are generated instead by resonant scattering of the disk continuum by a wind emerging from the disk. In the case of Z Cam, we are mainly looking through the wind projected against the disk, and hence the scattering removes light we would otherwise see. In the case of C IV λλ1548, 1551, the scattering region is somewhat larger than the disk. For C IV, we see absorption due to the portion of the wind which is mainly moving toward us (the short wavelength portion of the line) and emission from the portion of the wind which lies "outside" the disk which is mostly moving away (the long wavelength portion of the line). Lines with these general shapes were first seen and have been studied and modeled extensively in O stars. Because of this, they are generally known as P Cygni profiles. There, too, the lines arise due to an extended, high velocity wind. Unlike O stars, however, the winds of DNe are highly asymmetric, and the first attempts to model the effects of winds on the spectra of DNe are just now beginning (Vitello and Schlossman 1993; Knigge, Woods, and Drew 1995).

Among DNe, there are systems in which all of the FUV lines are in emission. This occurs when one observes a system which is nearly edge-on. As the inclination angle increases towards 90 degrees, the solid angle of the disk on the sky decreases, and the portion of the scattering wind which lies outside of the "light bulb" that is the disk increases, and, as a result, the emission portion of the line dominates. The extended nature of the line-forming region is especially clear in those systems in which the normal secondary star eclipses the disk. UX UMa was selected for observation on Astro-1 largely because it is such a system. As most commonly operated, HUT obtains a new spectrum every two seconds. Three spectra of UX UMa are shown in Figure 4. Each corresponds to a 500 s integration. The upper, middle, and lower panels of this figure

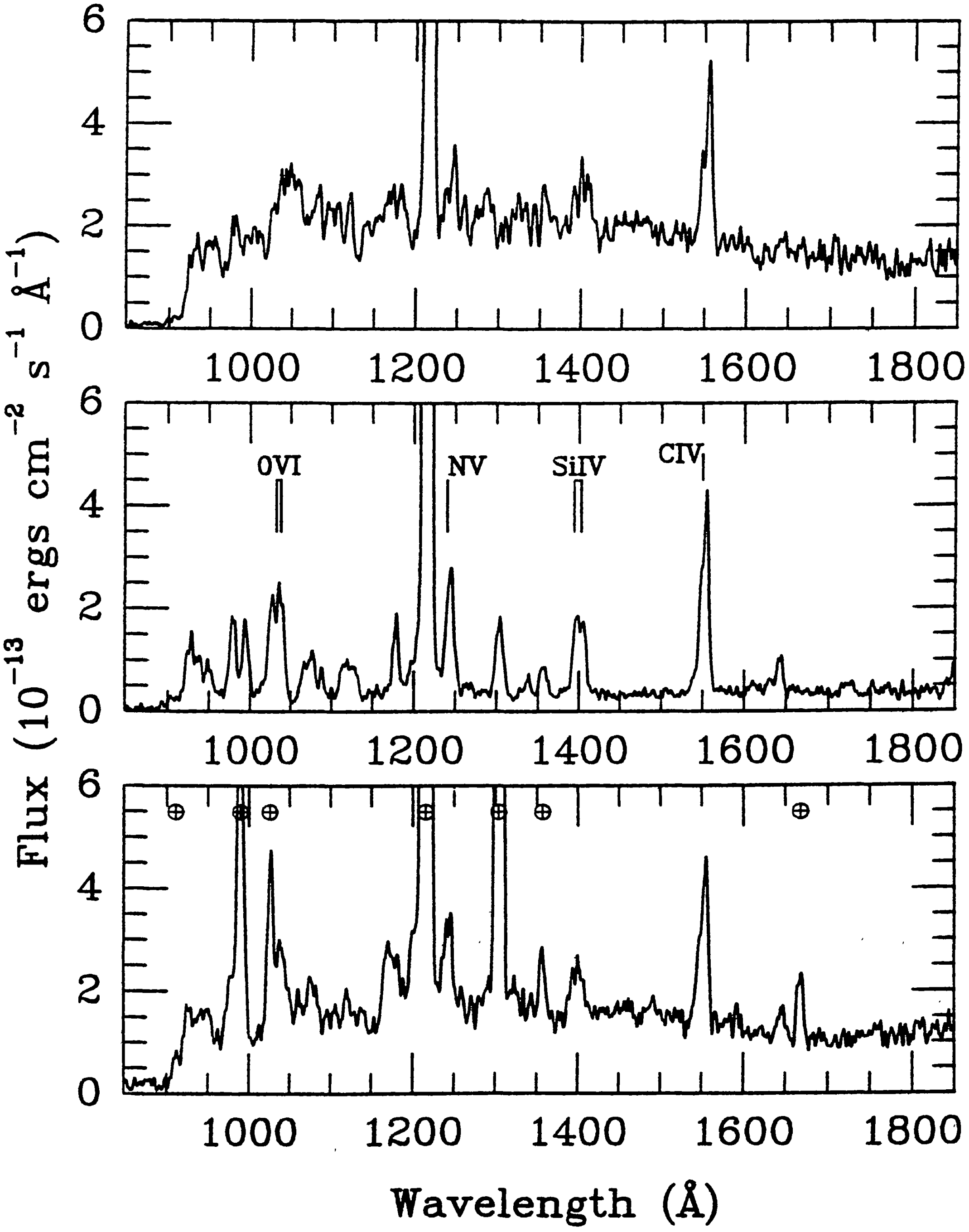

Figure 4. Spectra of UX UMa as observed on Astro-1 in 1990 December. The observations of UX UMa included an eclipse of the system. HUT transmits a spectrum to the ground every two seconds, and therefore it is straightforward to select time periods before, during, and after the eclipse. Airglow affects selected regions of the spectrum, as indicated in the after-eclipse (bottom) spectrum by the ⊕ symbols. Airglow affects this spectrum the most, because it was obtained as the shuttle was moving into orbital day. Collectively, the panels show that the disk of the system is occulted by the secondary star, but that the lines are not. As a result, it is clear that the line-producing regions are extended on a spatial scale that is comparable to or larger than the normal star in the system.

show spectra obtained just prior to, during, and just after the eclipse of the WD and inner disk. The resonance lines, essentially the same lines seen in Z Cam in absorption, are in emission in all three spectra of UX UMa. However, the extended nature of the line emitting region is most clear in the eclipse spectrum, since in that case the inner disk is occulted and does not contribute to the emergent flux.

## 4. Observations of dwarf novae in quiescence

According to the standard theory, "low" state disks of DNe are expected to be optically thin, cool, and hence faint in the FUV. As a result, the WD has generally been assumed to dominate the FUV spectra of DNe. At the time of the Astro-1 mission, IUE observations of several DNe in quiescence had been shown to be consistent with this hypothesis. In particular, IUE spectra of U Gem and VW Hyi exhibited the broad Lyman-$\alpha$ profile and the UV flux expected from a WD at their estimated distances (Panek and Holm 1984; Mateo and Szkody 1984). IUE spectra of other DNe did not always show the signature of the WD so clearly, but in many instances this was ascribed to a lack of S/N.

The spectra of the five DNe observed in quiescence during Astro-2 are shown in Figure 5. As the IUE observations had already indicated, detailed analyses of the HUT spectra of U Gem and VW Hyi provide strong support for the hypothesis that these two systems have spectra dominated by the WD. Not only does one see the continuum shape and the Lyman series of hydrogen as expected, but also narrow metal absorption lines. In fact, detailed model fits to the spectrum of U Gem indicate a temperature of 29,700 K, a WD radius of 5.4 x $10^8$ (D/90 pc) cm, consistent with that expected for a 1.05 $M_\odot$ WD, and near solar abundances in the atmosphere (Long *et al.* 1995). Metal lines are not normally seen in isolated WDs in this temperature range. Metals in the atmosphere of a WD tend to settle into the interior of the star on a timescale of 2–3 years due to the very high gravitational field, and, as a result, field WDs seldom show any lines except those of hydrogen or helium (cf. Michaud 1987). However, because the WD is accreting in a DN system, one expects to see metals in their atmospheres. As Wade, Hubeny and Polidan (1994) have recently emphasized, it is hard to distinguish a WD from a steady state accretion disk with low $\dot{m}$ using IUE, because accretion disks also have broad Lyman line profiles. However, the existence of narrow metal absorption lines in HUT (and HST [Long *et al.* 1994; Sion *et al.* 1995]) spectra of U Gem and VW Hyi is proof that we are seeing the WD, because lines from the disk should be Doppler broadened beyond the widths we see.

The spectra of other DNe observed in quiescence with HUT on Astro-2 do not show any obvious features of the WD. Instead, the spectra of SS Cyg, YZ Cnc, and WX Hyi can be characterized in terms of blue continua, on which are superposed broad (~10Å) emission features that can be identified with resonance lines such as S VI $\lambda\lambda$933,945, O VI $\lambda\lambda$1032, 1038, N V $\lambda\lambda$1239, 1243, Si IV $\lambda\lambda$1394, 1403, and C IV $\lambda\lambda$1548, 1551. Broad Lyman line profiles and narrow absorption lines appear to be absent from these spectra. Longward of Lyman $\alpha$, the HUT spectra of these objects resemble those obtained with IUE (see, e.g., La Dous 1990); the IUE spectra do not show clear evidence of the WD either. However, because HUT covers the wavelength range shortward of Lyman $\alpha$, it should have been more sensitive to the WD than IUE. If we insist that the WD dominate the continuum spectra, then the WDs in these systems have to be quite hot (>50,000 K in the case of SS Cyg;) so that the Lyman lines and the metal absorption lines would be hidden beneath the emission (and airglow) lines in the HUT spectra.

It seems far more likely that some other source of emission dominates the quiescent spectrum, and an obvious alternative is a hot region of the disk. A steady state accretion disk seems an unlikely culprit, however, since accretion rates comparable to those observed in outburst would be required to match the spectral shape, and since these

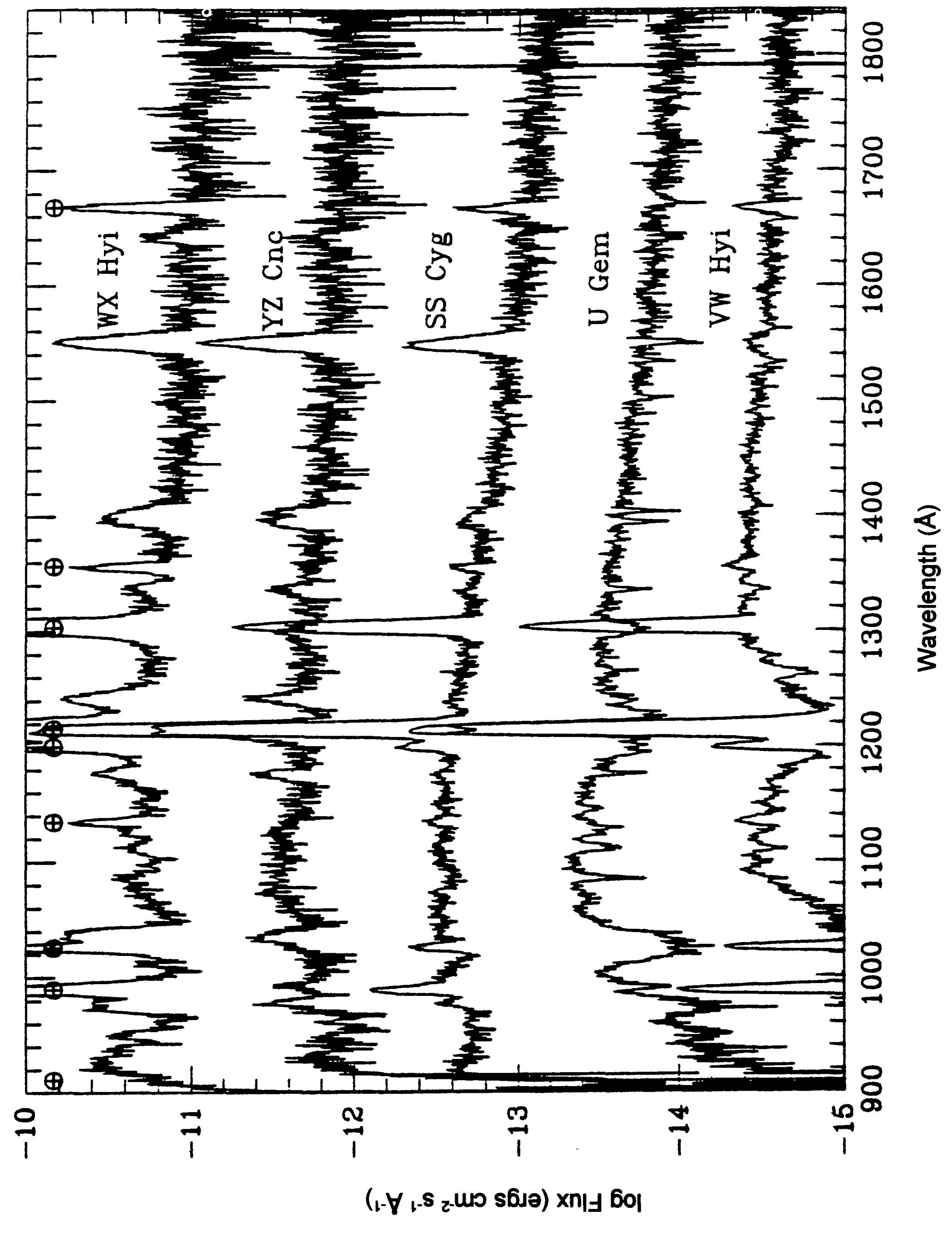

Figure 5. The spectra of all of the DNe observed in quiescence on Astro-2. The spectra of WX Hyi, YZ Cnc, and SS Cyg all show O VI λλ1032, 1038, N V λλ1239, 1243, and C IV λλ1548, 1551 in emission; the signatures of a WD are absent. On the other hand, the spectra of U Gem and VW Hyi have prominent Lyman α (1216 Å) profiles and show evidence of narrow absorption lines, as expected if the WD dominates the FUV spectra of these objects.

would produce far too much overall flux. Emission from the bright spot, where matter from the accretion stream encounters the accretion disk, is a possibility, but estimates of temperatures of the bright spot are generally on the order of 10,000 to 15,000 K, which is too low to account for the spectral shape. One idea that appears promising, but requires further investigation, is that X-ray and EUV radiation from the vicinity of the WD photoionizes and heats a surface layer on the disk to produce a hot corona. An X-ray-photoionized corona is interesting because it tends to produce emission lines and a hot, but optically thin, continuum. In fact, Ko *et al.* (1996) have recently carried out self-consistent calculations of the structure of such a corona and conclude they are able to account for the observed IUE line fluxes of several DNe, including SS Cyg and WX Hyi. The same models also appear to account for the C III λ977 and O VI λλ1032, 1038 line fluxes we observe in the HUT range (Ko 1995, private communication), although we are just now beginning a detailed comparison of these models with the HUT spectra.

## 5. Summary

The HUT spectra of DNe are the first set of FUV spectra with sufficient spectral resolution and signal-to-noise ratio to resolve emission and absorption lines in the wavelength range between Lyman α and the Lyman limit. The data demonstrate the importance of this spectral range for DNe, since models which fit the data in the IUE and HST wavelength ranges vary dramatically in the regions shortward of Lyman-α. In some systems (the WD-dominated quiescent DNe), the data appear to confirm the standard theory, but in others (the non-WD dominated quiescent systems and the high-state disk and wind systems), the analysis thus far has demonstrated as much as anything else the challenges we need to overcome to elucidate the physics of DNe. One of the especially pleasing aspects of these interesting objects is the close collaboration they engender between avid amateur and professional astronomers.

The Astro observations of CVs would not have been possible without the hard work of all my colleagues on the HUT project, especially the Principal Investigator, Arthur Davidsen; William Blair and John Raymond, who are working with me to analyze the HUT CV data; the NASA shuttle mission operations and support crew; and, as mentioned earlier, the amateur astronomical community. The HUT project and my work in it is supported by NASA contract 5-27000 to the Johns Hopkins University.

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