HUBBLE SPACE TELESCOPE/FOS SPECTROSCOPY OF VW HYDRI IN SUPEROUTBURST

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ABSTRACT

We present an analysis of two HST/FOS UV spectra of the SU UMa type dwarf nova, VW Hyi, obtained on 1993 October 24, ~5 days after the optical rise of a superoutburst. The absorption features in the first spectrum appear to consist of two components: a broad-winged component (with velocity width of ~3000 km s\(^{-1}\)) and a sharp core narrow component. This is the first time the narrow core is clearly resolved in superoutburst spectra of a dwarf nova system. The sharp core appears absent in the second spectrum obtained ~10 minutes later. The broader component is mainly from the accretion disk. By comparing the spectra with a grid of LTE model accretion disk atmospheres constructed with TLUSTY, SYNSPEC, and DISKSYN, we present two possible disk fits to the observed spectra: a steady state disk with solar abundance and ˙M = 3 \times 10^{-9} \, M_\odot \, yr^{-1} which can account for all the broad absorption features except for N v λ1240, and a model with a discontinuous T_{eff}(r) distribution in which there is a contribution to the N v λ1240 absorption feature. We provide arguments supporting the possibility that the sharp cores are due to gas streams in the system. We also point out the far less likely possibility that the sharp cores form in a hot, high-gravity atmosphere. The synthetic fitting results may imply that the hot matter is accreted from the inner part of the disk onto the surface of the white dwarf through a highly inhomogeneous gas flow. We relate this discussion to our FOS detection of highly asymmetric inverse P Cygni profile structure in the narrow stellar components at C iv λ1550.

Subject headings: accretion, accretion disks --- novae, cataclysmic variables --- stars: individual (VW Hydri) --- ultraviolet: stars --- white dwarfs

1. INTRODUCTION

VW Hydri is a relatively low inclination (i = 60°) dwarf nova (DN) system of the SU UMa class, in that it shows superoutbursts in addition to the normal outburst.

There are two types of models to explain the origin of the superoutburst phenomenon: (1) the models based on instabilities in the disk, either the pure thermal instability (Cannizzo 1994, and references therein) or the thermal-tidal instability (Osaki 1993, and the references therein), and (2) the enhanced mass transfer models (Vogt 1983; Osaki 1985). In the thermal instability model, the very sensitive dependence of opacity on disk temperatures at ~6000 K, the hydrogen ionization temperature, leads to a double-valued relation between disk surface density and temperature for the stable states of each annulus in the disk, a hot state with higher surface density and a temperature above the hydrogen ionization temperature, and a cool state with lower surface density and a temperature below the hydrogen ionization temperature (Faulkner, Lin, & Papaloizou 1983). During quiescence, the model suggests that the whole disk stays at the cool state. When the surface density of an annulus exceeds a critical value due to the accretion, it transits into a region where only the hot state is stable, so it is heated up to a higher temperature in a thermal timescale (<1 day for DNs). During the rise of an outburst, a transition wave quickly spread the hot state over other parts of the disk. The model predicts a rather sharp transition front, a boundary between the hot and cool region, whose thickness is \((HR)^{1/2}\), where \(R\) is the radius in the disk, and \(H\) the scale height of the disk (Cannizzo 1995), that propagates in the disk. The transition increases the mass accretion rate significantly. As a consequence, the disk starts to deplete in mass. Once the surface density falls below a second (smaller) critical value, the hot state ceases to exist. During the decline of the outburst, this transition front moves in the direction of decreasing the area of the hot state disk. In low ˙M accretion systems, a pure thermal instability model could produce a bimodal distribution of outburst durations (Huang & Wheeler 1989; Cannizzo 1994), in which the shorter outbursts may account for the observed normal outbursts and the longer ones may account for the superoutbursts. The thermal-tidal instability model attributes the normal outbursts to thermal instability and the superoutbursts to mainly tidal instability, which occurs in large disks in systems with low mass ratios. This model suggests that, after each normal outburst, the disk radius, \(R_{\text{out}}\), increases.

1 Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

2 Universities Space Research Association (USRA).
When $R_{in}$ exceeds a critical value (a certain fraction of the binary separation), the disk becomes elliptic and unstable under tidal instability (Whitehurst 1988; Hirose & Osaki 1989, 1990). A superoutburst is due to a sudden accretion of the material from the outer parts of the disk, perhaps triggered by a normal outburst, resulting from the enhanced tidal removal of the angular momentum. The enhanced mass transfer model involves a feedback between the accretion rate, the irradiation of the secondary, and the mass outflow rate. This feedback may, under certain conditions, be unstable, and lead to a limit-cycle behavior (Vogt 1983; Osaki 1985). In all of these models, the UV flux contribution from the white dwarf during outbursts is assumed to be negligible.

In all previous UV spectra of relatively low inclination SU UMa systems during superoutbursts, the low-dispersion *IUE* (Fabian et al. 1980; Szkoły 1982; Hassell et al. 1983; Hassell 1985; Verbunt et al. 1987; Szkoły, Osborne, & Hassell 1988; Wood et al. 1992; Cheng 1995) resolution was not sufficient to distinguish sharp linear narrow components, if present, versus the broader component from the accretion disk. The first UV spectra during VW Hya’s superoutburst were published in 1984 October by Verbunt et al. (1987) through the low-dispersion grating on *IUE*. They also obtained an accumulated high-resolution *IUE* spectra (with a resolution of 0.5 Å) during the same superoutburst, in which the narrow components in the resonance line of $N \nu \lambda 1240$ were partially resolved.

In the present work, we analyze two *HST/FOS/G130H* (with resolution 1 Å) UV spectra with high S/N ratio, obtained $\sim 5$ days after the optical rise of VW Hya’s 1993 October superoutburst. In the first of these two spectra, a narrow core component of the absorption lines is clearly resolved for the first time during a superoutburst of a DN.

### 2. OBSERVATIONAL DATA

We obtained two *HST/FOS/G130H* UV spectra of VW Hya on 1993 October 24, $\sim 5$ days after its optical rise to a superoutburst. In Figure 1, the observation time is marked on the optical light curve kindly provided by the American Association of Variable Star Observers. Using the updated photometric ephemeris given by van Amerongen et al. (1987), where the zero phase is defined as the midtime of the maximum in the light curve

$$HJD_{\text{max}} = 2,440,128.02407 \pm 0.00059 + 0.074271038E$$

we obtain the orbital phases of the system during the observations and list them in Table 1. The error in the orbital phase values is $\pm 0.02$. Phase 0.0, defined as above, corresponds to a $\sim 0.73$ phase in an ephemeris centered upon 0.0 as being an inferior conjunction of the secondary. The time separation of the mid-exposures is 10 minutes. The exposure time of the two spectra are 3 minutes and 50 s for the first exposure and 8 minutes and 9.99 s for the second exposure, which are 3.6% and 7.6% of the system’s orbital period (1.78 hr), respectively.

In the first spectrum (Fig. 2), the signal-to-noise ratio is larger than 30:1 in the wavelength range $\lambda > 1220$ Å and is $\sim 60:1$ near the $C iv \lambda 1550$ line. For the second spectrum (Fig. 3), these values are 45:1 and 90:1, respectively.

Both superoutburst spectra are characterized by very strong absorption features at $C iii \lambda 1180$, $Ly\alpha 1215$, $N \nu \lambda 1240$, $Si iii \lambda 1200$, $Si iv \lambda 1400$, and $C iv \lambda 1550$, which are broadened by the disk rotation, and a continuum level with a high degree of curvature. In the first of these two spectra, narrow cores in the absorption-line profiles, $N \nu \lambda 1240$ and $C iv \lambda 1550$ in particular, are clearly resolved for the first time during the superoutburst of a dwarf nova system. The sharpness of these line cores suggests formation in a more slowly rotating region while the extreme broadness of the wings suggest formation in a rapidly rotating disk. The line centers of these cores are redshifted by 150 km s$^{-1}$. The narrow cores in the second spectrum are not recognizable.

### 3. ACCRETION DISK MODELING

According to the standard theoretical picture of a DN outburst or superoutburst, the UV flux is dominated by the disk. In “pure” disk model, we assume that the flux is dominated by the disk emission. We cannot account for the observed narrowness of the line cores and ignore them in the

<table>
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</table>

**TABLE 1**

**LOG OF THE OBSERVED SPECTRA**

Note.—The orbital phases in the last column are given by van Amerongen et al. 1987, in which the phase 0.0 corresponds to a $\sim 0.73$ phase in an ephemeris centered upon 0.0 as binary inferior conjunction of the secondary.
Fig. 2.—The first HST/FOS UV spectrum we obtained near the peak of the superoutburst of VW Hya in 1993 October. For the first time, the narrow cores from a slowly rotating source (such as the white dwarf) at $\text{N} \, \lambda 1240$ and $\text{C IV} \, \lambda 1550$ are clearly resolved.

Fig. 3.—The second HST/FOS UV spectrum near the peak of the same superoutburst of VW Hya. Notice that the narrow core component is not recognizable.

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model disk fitting described below. The narrow cores are discussed separately in §§ 3.2 and 3.3 below.

We modeled the deep, broad metal absorption wings of the observed C II in 12180, N v in 1240, Si iv in 1300, Si iv in 1400, and C iv in 1550 by theoretical disk spectra. Since the disk during the superoutburst phase is optically thick (Kriz & Hubeny 1986), we do not construct detailed models of the vertical structure of the disk; instead we assume that the radiation from the disk surface may be well approximated by the equivalent model stellar atmosphere (Mayo, Wickramasinghe, & Whelan 1980; Wade 1984). The model atmosphere and emergent radiation are again constructed by TLUSTY and SYNSPEC, and the integration of all the contributions from the individual disk rings, taking into account the broadening effect of Keplerian disk rotation, was calculated with the code DISKSYN (Hubeny, unpublished).

We find that all the broad components in the observed features, except N v in 1240, can be well represented by a disk surface with $T_{\text{eff}} = 30,000$ K. Since the equivalent width of the N v in 1240 reaches a maximum when $T_{\text{eff}} = 80,000-100,000$ K, the observed deep N v in 1240 absorption, with its Doppler-broadened width, strongly indicates that there is such a component in the disk. However, LTE, optically thick models do not produce a large enough N v in 1240 equivalent width. In § 3.1, we describe two disk models: (1) a model with an 80,000 K inner annulus and a 30,000 K outer annulus and (2) a model with more continuous radial effective temperature distribution, $T_{\text{eff}}(r)$, in which the $T_{\text{eff}}$ of all annuli is much lower than 80,000 K.

3.1 Physical Parameters of the Disk Models

Based on the local thermodynamic equilibrium (LTE) disk atmosphere models with log $g = 5$, the metal absorption lines indicate that the spectrum is comprised of two effective temperature components. The deep N v in 1240 absorption is the signature of an 80,000-100,000 K disk atmosphere. The equivalent width (EW) of the N v in 1240 line reaches its maximum when $T_{\text{eff}}$ reaches 80,000-100,000 K, although it is too small to account for the observed EW, even with the nitrogen abundance modestly enhanced above the solar value. The other metal absorption lines are consistent with a 30,000 K disk atmosphere (see also Klare et al. 1982), with Si and C abundances modestly enhanced above solar. The profile of the Lyz absorption wing indicates that the UV flux is not dominated by either a 30,000 K disk atmosphere, which produces a much deeper absorption feature, or a 80,000-100,000 K disk atmosphere, which produces a much shallower 1216 absorption complex due mostly to Si in 1216 and Si in 1230. Instead it is a result of combining the two temperature components with comparable fractional contributions.

The observed UV flux level and the distance of the system constrain the UV emitting area on the disk. It seems natural at first to choose a disk in a steady state in which $T_{\text{eff}}$ varies gradually with radius. Choosing the mass of the white dwarf to be $0.6 M_\odot$, with a radius $R_{\text{wd}} = 8.7 \times 10^6$ cm, the $T_{\text{eff}}$ of a disk in a steady state with $M = 5 \times 10^{-5} M_\odot$ yr$^{-1}$ reaches 80,000 K near the white dwarf surface and 30,000 K at about $R_{\text{UV}} = 7.8 \times 10^6$ cm. The value of $R_{\text{UV}}$ is even larger if the $T_{\text{eff}}$ at the inner edge of the disk is higher than 80,000 K. However, as we will show immediately, the UV flux implied by this model gives a distance larger than the currently accepted value, $D = 90$ pc (Bailey 1981). We can estimate the upper limit of the radius of the disk UV emitting area, $R_{\text{UV}}$, by assuming a uniform $T_{\text{eff}}$ of 30,000 K in it and comparing it with the observed flux. The result is

$$D = 10 \text{ pc} \left(\frac{R_{\text{UV}}}{8.7 \times 10^6 \text{ cm}}\right)^2 - 1. \tag{1}$$

The upper limit $R_{\text{UV}}$, corresponding to $D = 90$ pc, is $\sim 7.8 \times 10^6$ cm, meaning that the radius of the UV emitting area in the accretion disk should be smaller than this.

The physical parameters for the best fit using our first model are $T_{\text{eff}} = 80,000$ K between $R = 1.0 R_{\text{wd}}$ and $1.7 R_{\text{wd}}$, and $T_{\text{eff}} = 30,000$ K between $R = 1.7 R_{\text{wd}}$ and $3.7 R_{\text{wd}} (\approx 3.2 \times 10^9$ cm), with abundances of Si = 15, N = 35, and C = 35 times their solar values, respectively (Fig. 4). The inner radius is determined by comparing the profile of the absorption line from the Keplerian disk model spectrum with the observed profile. The estimated uncertainty in the values of $R$ are $\sim 30\%$. Numerical experiments we performed show that if there were a significant UV contribution from annuli with $10,000 < T_{\text{eff}} < 30,000$ K, the global slope of the spectrum would be flatter than observed. Thus they are excluded from this model. The high metal abundances could be a result of CNO enhancement in the disk material due to repeated contamination of the secondary by past novae (Stahle & Kolb 1994) or to nuclear processing in the secondary.

A few implications for the accretion physics follow from this model.

First, as we have estimated, the accretion rate implied by the $T_{\text{eff}}$ in the inner disk (80,000 K), assuming that all the potential energy is released as radiation, is $\sim 5 \times 10^{-6} M_\odot$ yr$^{-1}$, rather high for a low accretion rate dwarf nova system such as VW Hydri. It is also much higher than the accretion rate in its 30,000 K outer neighbor ($\sim 10^{-9} M_\odot$ yr$^{-1}$). This may imply that the material at the inner edge of the disk is being rapidly evacuated. There is evidence that the outer part of an accretion disk during an outburst may be very close to a steady state, in which $T_{\text{eff}} \propto R^{-3/4}$ (Horne 1990). If the step function distribution of $T_{\text{eff}}$ revealed in our analysis is correct, then it may indicate that the disk is not in a steady state.

Second, in order for the white dwarf contribution to the UV continuum to be negligible, the surface temperature of the white dwarf should be at or lower than 30,000 K, thus being at most $10^4$ degrees higher than the white dwarf surface temperature of the system during its quiescence, $\sim 20,000$ K (Sion et al. 1995b; Huang et al. 1995a).

Third, the effective temperature distribution in the disk revealed by the model has a rather sharp boundary (with thickness $\ll R_{\text{wd}}$) between the hot region with $T_{\text{eff}} \geq 30,000$ K and the cooler region with $T_{\text{eff}} < 10,000$ K. This could be the first direct observational evidence of a transition wave front-like structure in a disk since the thermal instability model was suggested (Faulkner et al. 1983).

On the other hand, if we totally neglect the N v in 1240, then the disk models could have a more continuous $T_{\text{eff}}(r)$. After comparing a grid of steady state disk models with various values of $M$, we find that a model with $M = 3 \times 10^{-6} M_\odot$ yr$^{-1}$ and solar abundances also nicely reproduces all the broad absorptions except N v in 1240. The comparison between the model and the data is shown in Figure 5. Unfortunately, this model gives no absorption contribution at N v in 1240, whereas the two-temperature fit produces at least 50% of the observed absorption.

Compared to the first model, this model implies the following: (1) unlike the first model, it is in a steady state, consistent
Fig. 4.—The data in comparison with our first disk model, in which the UV emitting area in a Keplerian, optically thick disk has $T_{\text{eff}} = 80,000$ K between $R = 1.0$ and $1.7R_\text{ad}$ and $T_{\text{eff}} = 30,000$ K between $R = 1.7$ and $3.7R_\text{ad}$, with $N = 35$, $Si = 15$, and $C = 35$ times solar.

Fig. 5.—The data in comparison with our second disk model, which is in a steady state with $\dot{M} = 3 \times 10^{-9} M_\odot \text{ yr}^{-1}$ and solar composition.
with the currently accepted picture; (2) like the first model, the $T_{\text{eff}}$ of the white dwarf is $\leq 30,000$ K; and (3) the sharp discontinuity in $T_{\text{eff}}(r)$ is not needed in this model.

3.2. Is the Hot White Dwarf Exposed during Superoutburst?

Intrigued by the peculiar line structure appearing in the first spectrum, we were led to speculate that perhaps the combination of broad wings and very narrow cores could be explained by a two-component model: one from a hot white dwarf atmosphere and the other from the UV-emitting area of the disk.

It is clear that the sharp cores seen in Figure 2 cannot be produced in a velocity broadened disk profile. Therefore we seek line formation in a more slowly rotating region. Curiously we found that the narrow cores of the absorption lines were remarkably well replicated by a grid of solar composition model LTE stellar atmosphere spectra with TLUSTY (Hubeny 1998; Hubeny & Lanz 1995) and SYNSPEC (Hubeny, Lanz, & Jeffery 1994). In particular, we found that, at the FOS/G130H resolution and the S/N ratio of the spectrum, the line cores of both N v $\lambda$1240 and C iv $\lambda$1550 absorption could be reproduced quite well with an effective temperature of 80,000 K and log $g$ ranging from 7.0 to 8.0. The equivalent width (EW) of N v $\lambda$1240 remains basically the same when $T_{\text{eff}}$ is increased up to 100,000 K and will decrease for $T_{\text{eff}}$ outside this range. Since the C iv $\lambda$1550 absorption becomes significantly weaker at 100,000 K, we choose the $T_{\text{eff}}$ of the high-gravity atmosphere to be 80,000 K. The line profiles of the narrow cores of N v $\lambda$1240 and C iv $\lambda$1550 are sensitive to the abundance: raising the C and N abundances above solar in the white dwarf atmosphere would cause the two components of the doublets to merge, contrary to what we observe; lowering their abundances below solar would cause the depth of the overall absorptions to decrease. In Figure 6, we display a comparison between the observed line cores and synthetic profiles from a white dwarf model with oxygen = 0.1 solar and all other metal abundances having their solar values, $T_{\text{eff}}$ = 80,000 K, log $g$ = 7.5.

3.3. Origin and Disappearance of the Sharp Cores

As stated earlier, the narrow cores which appear in the first spectrum are not quantitatively accounted for in a disk model. Moreover, there is a clear change in the absorption lines over the 10 minute timescale between the first and second spectrum, in the sense that the sharp doublet lines cores at N v, C iv (and possibly Si iv) present in the first spectrum, appear to be completely absent in the second spectrum! Note that the N v and C iv lines in the second spectrum have lower central depths (i.e., their total equivalent widths are lower).

This behavior would support an origin for the narrow cores in the dilute gas of an accretion stream. In this scenario, the gas stream from the secondary in this relatively low inclination system is viewed against the disk to produce the observed absorptions. Alternatively, the gas stream could be at the inner edge of the disk viewed against the white dwarf as it infalls. Orbital phase-dependent, variable, narrow absorption features similar to the sharp cores reported here are also seen in the

![Figure 6](image)

**Fig. 6**—The data in comparison with our two-component model, which consists of a white dwarf with log $g$ = 7.5, $T_{\text{eff}} = 80,000$ K with oxygen abundance being 0.1 solar and other metals having their solar abundance, and a UV emitting area in a Keplerian, optically thick disk with $R_{\text{in}} = 1.0R_{\text{wd}}, R_{\text{out}} = 3.6R_{\text{wd}},$ Si = 15 times solar, C = 35 times solar and a uniform effective temperature of 30,000 K.
Algal binaries (E. F. Guinan, private communication) and clearly originate in the impact region of a gas stream with the transient Algol disks. The physical conditions of this gas stream are poorly known, and a quantitative treatment of the origin and physics of the sharp cores remains unexplained and beyond the scope of this paper.

If the sharp cores did in fact originate in a high-gravity atmosphere, then 10 minutes would seem too short for the diffusion timescale out of UV optical depth $\tau_{UV} = 1$. However, since the sharp line cores would form high in the accreted atmosphere of a 0.6 $M_\odot$ white dwarf (i.e., at small UV optical depth $< 1$) where $T = 80,000-100,000$ K, then the mass of the atmosphere at $\tau_{UV} = 1$ is only $\sim 10^{-16} M_\odot$. At the above temperatures, prevailing at small optical depth, diffusion/radiative forces theory is far less certain (Vauclair, Vauclair, & Greenstein 1979). In view of these considerations, it may be premature to regard a 10 minute diffusion timescale as being impossibly short, although such a short timescale is very improbable.

Therefore, by far the most likely explanation is that this change was caused by a rapid change in the column density of an emitting gas stream accreting onto the white dwarf. Given that the phase range of the first spectrum was 0.69–0.75 and, of the second spectrum 0.77–0.85 (where 0.0 corresponds to inferior conjunction of the secondary), an inhomogeneous distribution of accreting gas stream material (e.g., an accretion blob?) in front of the white dwarf (i.e., in the line of sight to the white dwarf) would account for the core disappearance. Since in the second spectrum, obtained after quadrature phase 0.75, the viewing angle encompasses more of the material between the white dwarf and Roche lobe-filling donor and a different aspect of the disk, we consider this a plausible possible explanation for the absence of the sharp cores in the second spectrum.

4. DISCUSSION AND SUMMARY OF RESULTS

We have analyzed the HST/FOS UV spectra obtained 5 days after the optical rise of VW Hya's superoutburst. In the first of the two spectra, narrow cores of the doublet absorption lines are clearly resolved for the first time. The variability timescale and narrowness of the cores suggest formation in a transient accretion stream near the white dwarf surface, but since the physical conditions of this accretion stream are not quantitatively known, the origin of the narrow cores is left unexplained in our model discussion. We note the remote possibility that the narrow cores are associated with formation in a hot ($T_{eff} = 80,000$ K) white dwarf atmosphere, whose far-UV flux contribution would be comparable to the disk. Our observations may provide the first direct observational evidence of the transition wave front structure suggested in the thermal instability model. The blueshifted inverse P Cygni profile at C IV $\lambda 1550$ may be manifesting an anisotropic inhomogeneous infalling gas flow onto the white dwarf.

There is possible evidence of an anisotropic, highly inhomogeneous flow from the inner part of the disk to the white dwarf surface along trajectories which are projected (along the line of sight) outside of the hot white dwarf stellar disk. An emission component near C IV $\lambda 1550$ appears in both spectra. The fact that our best-fit model spectrum does not reproduce this apparent emission component at all implies that the observed peak in the spectra is caused by physical mechanism(s) not included in our model spectra (e.g., infall, gas streaming). We tentatively identify this profile as an inverse P Cygni feature, which could be manifesting structured gas flow onto the white dwarf. In an isotropically infalling gas flow, there is no emission component of the inverse P Cygni profile centered near rest wavelength in the white dwarf's frame of reference, and the absorption component is redshifted. The observed emission component in the inverse P Cygni profile is blueshifted by 400 km s$^{-1}$ and is unlikely at rest relative to the white dwarf. This may imply a high degree of anisotropy of the highly inhomogeneous gas flow. With some uncertainty, our best fit indicates that the inner edge of the disk may be detached from the white dwarf surface. From the half-day delay of the UV outburst rise relative to the optical rise in many DN's, including VW Hya, there are suggestions (Livio & Pringle 1991; Meyer & Meyer-Hofmeister 1994) that the inner disk of VW Hya is detached from the white dwarf between the normal outbursts. So this highly inhomogeneous flow could be from the inner edge of the detached disk to the white dwarf surface.

Finally, our optically thick, LTE model fits do not reproduce the broad component of the N V $\lambda 1240$ well enough. Work using improved disk models, including the effects of non-LTE and vertical structure, is in progress, and the results will be reported in due time.

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