Hubble Space Telescope Far-Ultraviolet Spectroscopy of the Dwarf Nova VW Hydri in Superoutburst

JASON MERRITT
Department of Astronomy and Astrophysics, Villanova University, Villanova, PA; jason.merritt@villanova.edu

CHRISTOPHER NIGHT
Center for Astrophysics, Harvard University, Cambridge, MA; cnight@cfa.harvard.edu

AND
EDWARD M. SION
Department of Astronomy and Astrophysics, Villanova University, Villanova, PA; edward.sion@villanova.edu

Received 2006 August 31; accepted 2007 February 7; published 2007 March 2

ABSTRACT. We obtained three consecutive Hubble Space Telescope spectroscopic observations of a single superoutburst of the dwarf nova VW Hydri. The spectra cover the beginning, middle, and end of the superoutburst. All of the spectra are dominated by strong absorption lines due to C \textsc{iii} (1175 Å), Ly\textalpha (1216 Å), N \textsc{iv} (1238 and 1242 Å), S \textsc{ii} (1260–1565 Å), S \textsc{iii} (1300 Å), C \textsc{ii} (1335 Å), S \textsc{iv} (1394 and 1402 Å), and C \textsc{iv} (1548 and 1550 Å). We discuss the evolution of the far-UV energy distribution and line structure during the superoutburst. We note the absence of any P Cygni line structure in the Space Telescope Imaging Spectrograph spectra. Using state-of-the-art accretion disk models by Wade & Hubeny, we have determined for all three spectra accretion rates for two white dwarf masses, 0.55 and 0.8 \(M_\odot\). For both white dwarf masses, the accretion rate during superoutburst decreased by a factor of 2 from early to late in the superoutburst. The average accretion rate during superoutburst is \((3–6) \times 10^{-9} M_\odot\) yr\(^{-1}\), depending on the white dwarf mass.

1. INTRODUCTION

Dwarf novae (DNe) are a subclass of cataclysmic variable (CV) systems in which a white dwarf (WD; the primary) accretes hydrogen-rich matter from a low-mass, main-sequence–like star (the secondary), filling its Roche lobe. In these systems, the transferred gas forms an accretion disk around the WD. It is believed that the accretion disk is subject to a thermal-viscous instability that causes cyclic changes of the accretion rate. A quiescent stage marked by a low rate of accretion (\(\approx 10^{-11} M_\odot\) yr\(^{-1}\)) lasting weeks to months is interrupted by an outburst stage displaying a high rate of accretion (\(\approx 10^{-8} M_\odot\) yr\(^{-1}\)) lasting days to weeks. These outbursts (DN accretion event or nova-like high state) are believed to be punctuated every few thousand years or more by a thermonuclear runaway explosion, the classical nova (Hack & la Dous 1993).

VW Hyi is a key system for understanding DNe in general. It is one of the closest (Warner [1987] placed it at 65 pc), brightest, and best-studied examples of an SU UMa–type DN, and it lies along a line of sight with an exceptionally low interstellar column (Polidan et al. [1990] estimated the H \io column to be \(\approx 6 \times 10^{17} \text{ cm}^{-2}\)), which has permitted study of VW Hyi in nearly all wavelength ranges, including detection in the usually opaque extreme ultraviolet (Mauche 1996). Coherent and quasi-coherent soft X-ray oscillations and a surprisingly low luminosity boundary layer have been detected (Belloni et al. 1991; Mauche et al. 1991). VW Hyi is below the CV period gap near its lower edge, with an orbital period of 107 minutes and a quiescent optical magnitude of 13.8. Below the period gap, gravitational wave emission is thought to drive mass transfer, resulting in very low accretion rates during dwarf nova quiescence.

Systems of the SU UMa class undergo both normal DN outbursts and superoutbursts. For VW Hyi, the normal outbursts last 1–3 days and occur every 20–30 days, with peak visual magnitudes of 9.5. The superoutbursts last 10–15 days and occur every 5–6 months, with peak visual magnitudes reaching 8.5. The mass of the accreting WD was estimated to be 0.63 \(M_\odot\) (Schoembs & Vogt 1981), but more recently, a gravitational redshift determination yielded a larger mass \(M_{\text{wd}} = 0.86 M_\odot\) (Sion et al. 1997). The inclination of the system is \(\approx 60^\circ\) (Huang et al. 1996a, 1996b).

While the physical properties of the accreting white dwarf in VW Hyi, in addition to its response to heating by the outbursts and superoutbursts, have been derived from Hubble
**3. ANALYSIS**

In this section, we describe the procedure we followed to assess the contribution of the accretion disk and derive the accretion rate onto the white dwarf during the superoutburst. This procedure consists of comparing the observed *HST* STIS spectra of VW Hyi with a grid of theoretical accretion disk spectra for adopted system parameters and varying accretion disk parameters. The best-fit models are then obtained using a $\chi^2$ minimization fitting procedure. Details of the codes and the $\chi^2$ (per degree of freedom) minimization fitting procedures are discussed in detail in Sion et al. (1995) and Huang et al. (1996a) and are not repeated here.

For the accretion disk spectrum, we used the grid of accretion disk spectra computed by Wade & Hubeny (1998), who use a slightly different version of the code TLUSTY (Hubeny 1988), named TLUSDISK, to generate the theoretical spectrum of an accretion disk. The optically thick accretion disk model is made of a collection of rings. The disk models are computed assuming LTE and vertical hydrostatic equilibrium. The radial temperature structure in the disk is governed by the assumption of steady-state accretion equilibrium in which each annulus receives the same amount of mass as it loses (i.e., the disk gains as much mass from the Roche-lobe–filling donor star as the white dwarf accretes from the disk). Irradiation from external sources is neglected. Local spectra of disk annuli are computed, taking into account line transitions from elements 1–28 (H through Ni). Limb darkening as well as Doppler broadening and blending of lines are taken into account.

Before we carried out the model fits, we masked wavelength regions where strong resonance-line absorption due to zero volt resonance doublets appear in the *HST* spectra. The regions we masked in the fitting were N v (1228–1250 Å) and C iv (1530–1552 Å), in addition to any negative fluxes. For the accretion disk fits, we “fine-tuned” the derived accretion rate of the best-fitting disk model by changing the accretion rate in increments of 0.1 over the range 0.1–10, on the assumption that the disk fluxes scale linearly over that range.

**3.1. The Accretion Disk Models**

In superoutburst, a reasonable expectation is that the far-UV radiation should be dominated by the light of the luminous accretion disk. Moreover, since it is expected that at least during part of the superoutburst, the accretion disk should closely approximate a steady state, we explored whether an accretion
disk model would produce better agreement with the \textit{HST} STIS spectra. Although one expects the inner region of the accretion disk in VW Hyi to be optically thin during quiescence, this is not the case during outburst or superoutburst, which led us to assess how well optically thick steady-state disks can represent the observations.

In the present work, we used the grid of accretion disk spectra of Wade & Hubeny (1998), consisting of 26 different combinations of $M_{\text{WD}}$ (0.35, 0.55, 0.80, 1.03, and 1.21 $M_\odot$) and $M$ (log $M = -8.0$, $-8.5$, $-9.0$, $-9.5$, $-10.0$, and $-10.5$ $M_\odot$ yr$^{-1}$; see Table 2 in Wade & Hubeny [1998]). The spectra are presented for six different disk inclinations ($i$ 8.1°, 18.2°, 41.4°, 60.0°, 75.5°, and 81.4°). The model’s fluxes include the effects of limb darkening, the projection of fluxes as a function of the inclination angle, and are scaled to a distance of 100 pc, where the distance is related to the scale factor as

$$d = 100 \text{ pc}/S.$$  

For such a well-studied system as VW Hyi, we adopted widely used parameters in the literature. We fixed the distance $d = 65$ pc and the orbital inclination at $i = 60^\circ$, but assumed two values of the white dwarf mass, $M_{\text{WD}}$. The synthetic disk spectra were then fitted to the three superoutburst spectra by our $\chi^2$ minimization routine. The best-fitting accretion disk models are listed in Table 2, corresponding to $M_{\text{WD}} = 0.55$ and 0.8 $M_\odot$. We list in column (1) the part of the superoutburst in which the spectrum was taken, column (2) the white dwarf mass that was adopted, column (3) the adopted orbital inclination, column (4) the logarithm of the accretion rate, in solar masses per year, resulting from the best-fitting disk model, column (5) the $\chi^2$ value corresponding to the best fit, and column (6) the value of the increment that produced the best refined disk model fit (see §3).

The best-fitting accretion disk models to the three \textit{HST} spectra for both values of the white dwarf mass are displayed for the early spectrum (Fig. 1), the middle spectrum (Fig. 2), and the late spectrum (Fig. 3). All three spectra are well-fitted by steady-state accretion disk models, except for the observed continuum shortward of Ly\(\alpha\), where the theoretical disk flux overpredicts the observed flux. We discuss the results of these fits in the following section.

| Superoutburst Phase | WD Mass ($M_\odot$) | $i$ (deg) | log $M$ ($M_\odot$ yr$^{-1}$) | $\chi^2$ | $fM$ |
|---------------------|--------------------|----------|-----------------|--------|------|
| Early ............... | 0.55               | 60       | $-8.097(8 \times 10^{-8})$ | 2.905  | 0.8  |
|                     | 0.8                | 60       | $-8.386(4 \times 10^{-8})$ | 2.288  | 1.3  |
| Middle ............. | 0.55               | 60       | $-8.222(6 \times 10^{-8})$ | 2.581  | 0.6  |
|                     | 0.8                | 60       | $-8.500(3 \times 10^{-8})$ | 2.605  | 1.0  |
| Late ............... | 0.55               | 60       | $-8.459(3.5 \times 10^{-8})$ | 2.950  | 1.1  |
|                     | 0.8                | 60       | $-8.745(1.8 \times 10^{-8})$ | 3.036  | 1.8  |

**Table 2**

**Accretion Disk Model Fitting Results**

![Fig. 1.](image1)

**Fig. 1.**—Earliest of the three spectra, taken on 2000 May 20, near the peak of the superoutburst. The black line shows the best-fit model, with a mass of 0.8 $M_\odot$, an accretion rate of $4 \times 10^{-9}$ $M_\odot$ yr$^{-1}$, and an inclination of 60°. The model flux shows an excess over the observed flux at the shortest wavelengths. The horizontal lines in the lower part of the figure indicate the wavelength regions that were masked out in the fitting.

**4. SUMMARY AND CONCLUSIONS**

The high-quality \textit{HST} STIS data, together with the currently accepted orbital inclination and a reasonable distance (65 pc) for VW Hydri, enabled a determination of the accretion rate during a superoutburst as a function of time within the superoutburst. For assumed white dwarf masses $M_{\text{WD}} = 0.55$ and 0.8 $M_\odot$, the derived average accretion rates during superoutburst are $6(\pm 1) \times 10^{-9}$ and $3(\pm 1) \times 10^{-9} M_\odot$ yr$^{-1}$, respectively. All of the best-fitting models show a flux excess relative to the observations. This flux deficit relative to the models, shortward of Ly\(\alpha\), may be due to the possibility that

![Fig. 2.](image2)

**Fig. 2.**—Second spectrum, taken on 2000 May 22, as the flux was declining after the superoutburst. The black line shows the best-fit model, with a mass of 0.8 $M_\odot$, an accretion rate of $3 \times 10^{-9}$ $M_\odot$ yr$^{-1}$, and an inclination of 60°.
Fig. 3.—Third and final spectrum, taken on 2000 May 25, near the end of the superoutburst. The black line shows the best-fit model, with a mass of $0.8 M_\odot$, an accretion rate of $2 \times 10^{-9} M_\odot \text{yr}^{-1}$, and an inclination of $60^\circ$. Toward the end of the superoutburst, the accretion rate has declined by a factor of 2.

the accretion disk in VW Hyi is modestly truncated; hence, having a cooler inner disk region than the untruncated accretion disk model. The accretion rate late in the superoutburst has declined by a factor of 2 relative to the accretion rate early in the superoutburst.

Huang et al. (1996a) modeled an HST Faint Object Spectrograph (FOS) G130H spectrum of VW Hyi taken roughly 5 days after the optical rise to superoutburst in 1993 October. This was approximately the same amount of time that elapsed before the first STIS E140M spectrum was taken during the 2000 May superoutburst reported in this paper. For a white dwarf mass of $M_{WD} = 0.6 M_\odot$ and a distance of 90 pc, Huang et al. (1996a) found a best-fitting disk model accretion rate of $3(\pm 1) \times 10^{-9} M_\odot \text{yr}^{-1}$, while in the present paper, with $d = 65$ pc, accretion rates of $8(\pm 1) \times 10^{-9}$ and $4(\pm 1) \times 10^{-9} M_\odot \text{yr}^{-1}$ were determined for white dwarf masses $M_{WD} = 0.6$ and $0.8 M_\odot$, respectively. The same sharp cores of N v and C iv detected by Huang et al. (1996a) are seen at N v in Figures 1, 2, and 3 of this paper, but not at C iv. In Huang et al., the sharp cores at C iv reveal a hint of inverse P Cygni structure, as though either infall onto the white dwarf or superposition of an inhomogeneous accretion stream is being seen. The C iv profile in the STIS E140M spectra reported in this paper do not reveal the resolved sharp doublet cores in C iv, but rather a merged sharp core.

Given our derived accretion rates, it may be possible to carry out quasi-static evolutionary model simulations at these rates to compare with the amount of white dwarf cooling evident from model analyses of postoutburst and postsuperoutburst FUV spectra. We leave this for a future exploration.

This work was supported by NSF grants AST 05-07514 and NASA grant NNG 04GE78G, and by summer undergraduate research support from the Delaware Space Grant Consortium.

REFERENCES

Belloni, T., et al. 1991, A&A, 246, L44
Hack, M., la Dous, C. 1993, Cataclysmic Variables and Related Objects (NASA SP-507; Washington: NASA)
Huang, M., Sion, E. M., Hubeny, I., Cheng, F., & Szkody, P. 1996a, ApJ, 458, 355
———. 1996b, AJ, 111, 2386
Hubeny, I. 1988, Comput. Phys. Comm., 52, 103
Mauche, C. W. 1996, in 158th IAU Colloq., Cataclysmic Variables and Related Objects, ed. A. Evans & J. H. Woods (Dordrecht: Kluwer), 243
Mauche, C. W., Wade, R. A., Polidan, R. S., van der Woerd, H., & Paerels, F. B. S. 1991, ApJ, 372, 659
Polidan, R. S., Mauche, C. W., & Wade, R. A. 1990, ApJ, 356, 211
Schoembs, R., & Vogt, N. 1981, A&A, 97, 185
Sion, E. M., Cheng, F. H., Sparks, W. M., Szkody, P., Huang, M., & Hubeny, I. 1997, ApJ, 480, L17
Sion, E. M., Szkody, P., Cheng, F. H., & Huang, M. 1995, ApJ, 444, L97
Wade, R. A., & Hubeny, I. 1998, ApJ, 509, 350
Warner, B. 1987, MNRAS, 227, 23