The Fall and the Rise of X-Rays from Dwarf Novae in Outburst: 
RXTE Observations of VW Hydri and WW Ceti

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ABSTRACT. In a dwarf nova, the accretion disk around the white dwarf is a source of ultraviolet, optical, and infrared photons, but is never hot enough to emit X-rays. Observed X-rays instead originate from the boundary layer between the disk and the white dwarf. As the disk switches between quiescence and outburst states, the 2–10 keV X-ray flux is usually seen to be anticorrelated with the optical brightness. Here, we present RXTE monitoring observations of two dwarf novae, VW Hyi and WW Cet, confirming the optical/X-ray anticorrelation in these two systems. However, we do not detect any episodes of increased hard X-ray flux on the rise (out of two possible chances for WW Cet) or the decline (two for WW Cet and one for VW Hyi) from outburst, attributes that are clearly established in SS Cyg. The addition of these data to the existing literature establishes the fact that the behavior of SS Cyg is the exception, rather than the archetype as is often assumed. We speculate on the origin of the diversity of behaviors exhibited by dwarf novae, focusing on the role played by the white dwarf mass.

1. INTRODUCTION

The outburst cycles of dwarf novae are understood as being due to thermal instability in the accretion disk around the white dwarf primary. In the simplest form of the theory, the disk traces an S-curve in the surface density ($\Sigma$)-effective temperature ($T_{\text{eff}}$) plane, with two stable branches. The mass transfer rate from the Roche-lobe filling secondary is sufficiently low in dwarf novae that the disk is usually in the quiescent branch in which $T_{\text{eff}}$ is low and hydrogen is mostly neutral. The disk is completely out of steady state, with accretion rate $\dot{m} = \frac{n_r \delta r}{\Sigma}$, so the accretion rate onto the white dwarf is low and $\Sigma$ increases over time. When it reaches the end of the quiescent branch, the disk jumps to the outburst branch in which the disk is hot and ionized and efficiently transports matter onto the white dwarf. See Lasota (2001) for a comprehensive review of the disk instability theory.

Dwarf novae are well-known sources of 2–10 keV X-rays, particularly during quiescence, but also in outburst. Since the accretion disk surrounding a white dwarf is never hot enough to generate X-rays, even during outburst, we must seek their origin elsewhere. A widely held view is that they originate in an equatorial boundary (Patterson & Raymond 1985a, 1985b), which connects the Keplerian accretion disk to the slowly rotating white dwarf surface. The detection of a narrow X-ray eclipse in OY Car (e.g., Wheatley & West 2003) and other deeply eclipsing dwarf novae in quiescence is consistent with this picture, while casting doubt on the “coronal siphon flow” model of Meyer & Meyer-Hofmeister (1994), which posits a hot, spatially extended X-ray emitting region around the white dwarf. In the rest of this article, we therefore proceed with the boundary-layer model as the basis of our interpretation.

In this view, the quiescent boundary layer is optically thin and hot ($kT \sim 10$ keV), while the outburst boundary layer is predominantly optically thick (with $kT \sim 10$ keV), but also contains an optically thick region. Coordinated multiwavelength observations of dwarf novae can therefore reveal the physical states of the accretion disk and the boundary layer, at different points during the outburst cycle. Previous campaigns during a single outburst include those on SS Cyg (Wheatley et al. 2003), VW Hyi (Wheatley et al. 1996; Hartmann et al. 1999), and GW Lib (Byckling et al. 2009). These three campaigns in particular had dense-enough X-ray coverage through the outburst to enable these authors to study the time evolution of X-ray flux. Campaigns that covered multiple outburst cycles include those on YZ Cnc (Verbunt et al. 1999), V1159 Ori (Szkody et al. 1999), and SU UMa (Collins & Wheatley 2010). Here, we present our analysis of two sets of X-ray observations taken with the Proportional Counter Array (PCA) instrument (Jahoda et al. 1996) on board RXTE (Bradt et al. 1993): one of a superoutburst of VW Hyi and the other of WW Cet obtained over 3 months and containing two outbursts. These data sets are well suited to
the study of transitions of the X-ray emissions from quiescence to outburst and back.

2. OBSERVATIONS AND DATA REDUCTION

VW Hyi is a dwarf nova with a quiescent magnitude of \( V \sim 14 \) and an orbital period of 1.78 hr (Schoembs & Vogt 1981). In addition to the normal outbursts (once every 20–30 days), it has superoutbursts once every 180 days or so, which is the defining characteristic of the SU UMa subclass. The superoutbursts are brighter (\( V \sim 8.5 \) vs. 9.5) and last longer (10–14 days vs. 3–5 days), and they are characterized by superhumps, which are photometric variations at a period slightly longer than the orbital period (\( \sim 1.84 \) hr). Smith et al. (2006) estimated its white dwarf to be \( 0.71^{+0.18}_{-0.20} \ M_\odot \) based on a refined measurement of the gravitational redshift in the photospheric absorption line. Pringle et al. (1987) contains further details of VW Hyi.

VW Hyi was observed 42 times with RXTE between 1996 May 2 13:08 UT and 1996 May 16 23:55 UT (obsIDs 10041-02-01-00 through 10041-02-44-00, except 10041-02-31-00 and 10041-02-36-00), with a typical exposure of 2 ks each and separated by 4–16 hr. According to the AAVSO database, VW Hyi went into an outburst around JD 2,450,201.0 (1996 April 27 at 12:00 UT), brightening from magnitude 13.5 to \( \sim 9 \) in about 6 hr, and returned to quiescence (\( V > 13 \)) at about 2,450,216.25 (May 12 at 18:00 UT). Both the peak magnitude (\( V < 9 \)) and the duration establish this as a superoutburst, even though we do not have direct confirmation through the detection of superhumps. Thus, the RXTE observations started \( \sim 5 \) days after the start of a superoutburst of VW Hyi and continued \( \sim 4 \) days after its return to quiescence.

WW Cet is a dwarf nova with a 4.22 hr orbital period, with an average quiescent magnitude of \( V = 13.9 \) and reaching \( V \sim 11 \) in outburst, it also shows occasional low states as faint as \( V = 16.2 \) (Ringwald et al. 1996). Hawkins et al. (1990) carried out radial velocity measurements of the accretion disk and the secondary, and assuming a main-sequence companion, estimated the white dwarf mass to be \( 0.83 \pm 0.16 \ M_\odot \) for this system. Recently, Simonsen & Stublings (2011) have detected a standstill in WW Cet for the first time, establishing this to be a Z Cam type of dwarf nova. However, at the time of our observations, it displayed the normal quiescence-outburst behavior of dwarf novae.

WW Cet was observed every day for 90 consecutive days between 2002 August 14 and 2002 November 11 (obsIDs 70005-01-01-00 through 70005-01-90-00), with a typical daily exposure of 2.5–3.5 ks. On nine occasions, the observations were split into two subexposures (October 25, 26, 27, 29; November 1, 2, 3, 10, and 11), and once (November 8) into three subexposures, which were correspondingly shorter. Treating them separately, we therefore have 101 observations of WW Cet over a 3 month period. According to the AAVSO database, WW Cet went into outburst twice during this campaign; we will describe them in more detail subsequently. The last outburst before 2002 August 14 was poorly covered but appears to have ended on or around July 12; the first outburst after November 11 started on December 10.

We analyzed the Standard2 binned-mode data (i.e., 129 channel spectra accumulated every 16 s) using HEASoft version 6.6.3. We screened the data using the following screening criteria: angular separation between target and the pointing direction of less than 0.05°, elevation angle of greater than 5°, time since the last South Atlantic Anomaly passage of greater than 25 minutes, and low electron contamination (ELECTRON2 of less than 0.1). PCA background was estimated using the L7 faint model. VW Hyi observations were taken with three to five of the five active PCUs. Observations of WW Cet, on the other hand, were obtained with two or three active PCUs. This, however, included PCU0, which by 2002 had lost its propane layer, leading to a larger uncertainty in the background modeling. We therefore excluded PCU0 data from further analysis for WW Cet (but not for VW Hyi).

Since the PCA has little sensitivity below 2.5 keV, and these sources are not significantly detected above 10 keV, we analyzed the background-subtracted rate in the 2.5–10 keV range. Since our main interest is the variability through an outburst or through an interoutburst period, our main data products were the average count rates per active PCU per pointing. We also performed spectral fitting for completeness, even though the data quality is rather limited for this purpose.

3. RESULTS

3.1. VW Hyi

We present the X-ray and visual light curves of VW Hyi in Figure 1. There is a clear dichotomy in the observed RXTE count rates: the first 30 points (taken during the 10 day period covering the superoutburst peak and decline) are at \( 0.25 \pm 0.04 \) c s\(^{-1}\) PCU\(^{-1}\) (mean and standard deviation). The last 12 points, taken after the return to quiescence, are at \( 0.67 \pm 0.08 \) c s\(^{-1}\) PCU\(^{-1}\).

We have fitted the average quiescent spectra of VW Hyi using a single-temperature MEKAL model (Mewe et al. 1985, 1986; Liedahl et al. 1995; Kaastra et al. 1996) with a Gaussian emission line at 6.4 keV and a neutral absorber. This gives an acceptable fit (\( \chi^2 = 0.74 \)) with \( kT = 6.4 \pm 1.3 \) keV, metallicity 0.44 ± 0.22 solar, a 240 eV equivalent width line at 6.4 keV, and a 2–10 keV flux of \( 7.3 \times 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\). Although multitemperature models are more physical and known to be required in fitting higher-quality X-ray data on VW Hyi (Pandel et al. 2005) and result in even lower \( \chi^2 \) with the RXTE data, they are not required, due to the modest spectral resolution of the PCA.

We have also attempted spectral fits to the average superoutburst spectrum of VW Hyi, for completeness. Although our analysis indicates a nominal 2–10 keV flux of \( 2.7 \times 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\), this is below the confusion limit for the PCA data of \( 4 \times 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\) (Jahoda et al. 2006) set
by the Poissonian fluctuation in the cosmic X-ray background within the PCA field of view in the direction of VW Hyi. Therefore, while we can be confident that VW Hyi was fainter in superoutburst by $0.42 \pm 0.09$ $c$ s$^{-1}$ PCU$^{-1}$ (approximately $5 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$) than in quiescence, we cannot determine the actual flux level or the spectral shape during superoutburst from our data.

The X-ray state transition took place in 17 hr. The last superoutburst obsID is 10041-02-30-00, with good exposure between 05:09 and 05:37 UT on 1996 May 12. The average 2.5–10 keV count rate is 0.20 $c$ s$^{-1}$, and there is no significant change in brightness within the exposure. The first quiescence obsID is 10041-02-32-00, which started at 21:10 UT on the same day, by which time it was already at 0.57 $c$ s$^{-1}$. During this interval, VW Hyi declined from $V \sim 12.5$ (at 07:24 UT) to $\sim 13.3$ (at 18:37 UT), close to the quiescent level.

Our best-fit quiescent model predicts an EXOSAT medium-energy experiment rate of 0.6 $c$ s$^{-1}$ per half-array, which is in reasonable agreement with the observations of van der Woerd & Heise (1987). It also predicts 3 $c$ s$^{-1}$ with the Ginga Large Area Counter (LAC), somewhat lower than the observed rate of $\sim 5$ $c$ s$^{-1}$ of (Wheatley et al. 1996). This Ginga observation also included the outburst to quiescence transition. In this case, the strong variability within each orbit makes it harder to judge the exact duration of transition (see their Fig. 2), but it was definitely shorter than 0.4 days, and was arguably as short as 0.1 days. In the latter interpretation, the last $\sim 0.3$ days of Ginga data may be interpreted as showing a slight rise from the initial quiescent level of $\sim 4$ $c$ s$^{-1}$ to $\sim 7$ $c$ s$^{-1}$ during some orbits.

3.2. WW Cet

We present the X-ray and visual light curves of WW Cet in Figure 2. Similar to the case of VW Hyi, WW Cet shows a significant decrease in the X-ray flux level during the two outbursts. The average quiescent count rates and standard deviations are 0.65 ± 0.05 on August 14 and 15, 0.70 ± 0.07 during August 23–October 12, and 0.61 ± 0.12 during August 26–November 11. During outburst, the background-subtracted count rates are consistent with zero (0.00 ± 0.02 on August 17–21 and 0.00 ± 0.03), well within the systematic uncertainty in the background level.

The quiescent spectrum of WW Cet can be described using a single-temperature model ($\chi^2_r = 0.82$) with $kT = 7.0 \pm 0.5$ keV, metallicity 0.50 ± 0.10 solar, a 67 eV equivalent width line at 6.4 keV, and a 2–10 keV flux of $8.2 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$. The quiescent flux is clearly not constant, but there is a sufficiently high level of point-to-point variability that we cannot comment on any systematic trends. Most importantly, we have fitted a constant and a linear line to the fully covered interoutburst period between August 23 and October 12. We
obtain a lower $\chi^2$ with the constant model: That is, we do not detect a secular trend in the quiescent X-ray flux of WW Cet.

We appear to have resolved the X-ray transitions into and out of outbursts in WW Cet. The count rates and statistical errors on August 16, August 22, October 13, and October 22 are $0.46 \pm 0.04$, $0.41 \pm 0.04$, $0.16 \pm 0.04$, and $0.14 \pm 0.04$, intermediate between the quiescent and outburst levels. We therefore investigate the relative timing of X-ray and optical transitions in more detail.

The August 16 X-ray data were taken between 13:17 and 14:11 UT. In the optical, AAVSO reports visible data on August 16 at 16:22 UT ($V = 14.5$) and on August 17 at 12:30 UT ($V = 11.2$). Thus, it appears that X-ray decline began before a significant rise in the optical. The intermediate X-ray point at the end of this outburst was taken on August 22 between 10:09 and 10:54 UT, which unfortunately falls in a significant gap in the optical coverage (between August 21 12:34 UT, when WW Cet was at $V = 13.34$, and August 24 16:13 UT at $V = 14.96$), but was, in any case, close to the return to quiescence. The October 13 X-ray data were taken between 13:27 and 14:21 UT. In the optical, WW Cet was already at $V = 11.5$ at 10:15 UT. The October 25 X-ray data were taken between 20:00 and 20:13 UT, which is after it was seen at $V = 15.3$ at 06:24 UT; therefore, it appears that the X-ray recovery took place only after the system had already returned to quiescence.

### 3.3. Comparisons with Past Campaigns

In terms of the boundary-layer behavior, the single best observed outburst of any dwarf novae may well be the 1996 October outburst of SS Cyg (Wheatley et al. 2003). This outburst had the following features:

1. During the rise of the outburst, the “hard” (>2 keV) flux initially increases (enhancement—rise).
2. The optically thick boundary layer develops, as evidenced by the sudden increase in the EUV flux and a simultaneous drop in the hard X-ray flux is delayed relative to the optical rise (X-ray delay).
3. Through the bulk of the outburst, the hard X-ray flux is lower than in quiescence (X-ray suppression).
4. During this period, the X-ray spectrum is softer than in quiescence (spectral softening).
5. The optically thick boundary layer disappears near the end of the optical decay, as evidenced by decreased EUV flux and increased hard X-ray flux (recovery at late decline).
6. The hard X-ray flux remains elevated for a period after the recovery (enhancement—decline).

It is worth examining the body of data accumulated to date to determine if these features should be taken as the paradigm in which to interpret observations of outbursts of other dwarf novae, for which only lesser quantity and/or quality of data are available. We have therefore searched the literature for descriptions of well-observed outbursts and judged how many of these features are shared by other outbursts.

SU UMa shares four of the six characteristics with SS Cyg according to Collins & Wheatley (2010), but failed to show X-ray enhancements at rise or in decline. In the case of VW Hyi, the X-rays are suppressed during outburst and recover at late decline. However, the RXTE campaign did not cover the
rise, and the ROSAT data of Wheatley et al. (1996) suggest little or no X-ray delay. Hartmann et al. (1999) observed spectral softening in VW Hyi in outburst in their BeppoSAX data. However, elevated X-ray flux levels have not been definitively detected at rise or late decline, although the Ginga LAC data allow the possibility of enhancement at late decline. As for WW Cet, we arrive at the same set of answers as for VW Hyi based on the RXTE campaign. As for U Gem, the X-rays are in fact enhanced during outburst (Mattei et al. 2000), and the outburst spectral shape is complex enough to preclude a simple answer to the “softening” question (Güver et al. 2006). GW Lib is another dwarf nova with a higher X-ray flux during outburst (Byckling et al. 2009), which was also harder. We summarize these results in Table 1.

In addition, Szkody et al. (1999) contains an intriguing report that the hard X-ray flux may have recovered during the middle of two superoutbursts of V1159 Ori. However, the quality of the nonimaging RXTE data of V1159 Ori is rather low, so we have not included this object in our table. Similarly, while Verbunt et al. (1999) show that the X-ray fluxes are suppressed during outburst in YZ Cnc, this campaign is less conclusive regarding other questions.

4. DISCUSSION AND CONCLUSIONS

This article adds to the literature of X-ray observation of dwarf novae during outbursts. Through these observations and analyses, common, if not universal, patterns are emerging. In the majority of dwarf novae, the X-ray flux is suppressed during outburst. This is true of four out of six systems listed in Table 1 and probably also true in YZ Cnc and (largely) in V1159 Ori, as well as other dwarf novae for which one or two X-ray spectra have been obtained in outburst (e.g., Z Cam; see Baskill et al. 2001). We interpret this as the consequence of an optically thick boundary layer, which radiates most of the boundary-layer luminosity during outburst. In this majority, the X-ray spectrum also appears to become softer in outburst. We propose Compton cooling as a possible mechanism for this, as Nelson et al. (2011) postulated for the quiescent X-ray emission from RS Oph.

Standard textbooks such as by Frank et al. (2002) convincingly show that Compton cooling cannot be important in cataclysmic variables if the seed photons are from the heated surface of the white dwarf in a one-zone accretion. However, the boundary layer in dwarf novae in outburst has at least two zones. At the equator, the boundary layer is optically thick,

| Object   | X-ray suppression | Spectral softening | X-ray delay | Recovery at late decline | Enhancement—rise | Enhancement—decline |
|----------|------------------|--------------------|-------------|--------------------------|------------------|---------------------|
| SS Cyg   | Yes              | Yes                | Yes         | Yes                      | Yes              | Yes                 |
| SU UMa   | Yes              | Yes                | Yes         | Yes                      | No               | No                  |
| VW Hyi   | Yes              | Yes                | Yes         | Yes                      | No               | Maybe              |
| WW Cet   | Yes              | ?                  | No?         | Yes                      | Yes              | No                  |
| U Gem    | No               | ?                  | Yes         | Yes                      | ?                | ?                   |
| GW Lib   | No               | No                 | ?           | ?                        | ?                | ?                   |

### TABLE 2

**CRITICAL MASS ACCRETION RATE**

| Object   | Distance \(^a\) (pc) | Primary mass \(^b\) \((M_\odot)\) | \(L_{\text{X, peak}}\) \(^c\) \((\text{ergs s}^{-1})\) | \(\dot{m}\) \(^d\) \((\text{g s}^{-1})\) | Fiducial \(M_\text{dot}\) \(^e\) \((\text{M}_\odot)\) |
|----------|----------------------|------------------------------------|---------------------------------|----------------|-----------------|
| SS Cyg   | \(165^{+13}_{-11}\)  | \(0.81 \pm 0.19\)                | \(1.2 \times 10^{31}\)         | \(1.0 \times 10^{30}\) | 1.0             |
| SU UMa   | \(260^{+100}_{-50}\) | \(0.71^{+0.08}_{-0.05}\)         | \(2.6 \times 10^{31}\)         | \(4.2 \times 10^{32}\) | 0.75            |
| VW Hyi   | 65                   | \(0.83 \pm 0.16\)                | \(8.1 \times 10^{30}\)         | \(1.3 \times 10^{31}\) | 0.83            |
| WW Cet   | \(146 \pm 25\)       | \(1.20 \pm 0.05\)                | \(7.3 \times 10^{31}\)         | 1.20           |                 |
| U Gem    | 100 \(\pm 4\)        | \(8.4 \times 10^{32}\)           | \(7.0 \times 10^{32}\)         | 1.0            |                 |

\(^a\) Distances are taken from Harrison et al. (2004) for SS Cyg and U Gem, Thorstensen (2003) for SU UMa and GW Lib, Warner (1987) for VW Hyi, and Sproats et al. (1996) for WW Cet.

\(^b\) The white dwarf masses are taken from Bitter et al. (2007) for SS Cyg, Smith et al. (2006) for VW Hyi, Echevarria et al. (2007) for U Gem, and van Spaandonk et al. (2010) for GW Lib. There is no estimate in the literature for SU UMa, while the numbers for WW Cet use the mass ratio obtained by Hawkins et al. (1990) and assume a main-sequence secondary.

\(^c\) The peak X-ray luminosities are taken from Wheatley et al. (2003) for SS Cyg, Collins & Wheatley (2010) for SU UMa, Pandel et al. (2005) for VW Hyi, Echevarria et al. (2006) for U Gem, and Byckling et al. (2010) for GW Lib. These values are then used by the same authors to infer the highest accretion rate through the optically thin boundary layer for the fiducial white dwarf mass.

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emitting copious soft photons; at somewhat higher latitude, the boundary layer is optically thin but subject to these external seed photons (see Fig. 8 of Patterson & Raymond 1985a). Since the number of soft photons greatly exceeds that of the hot electrons (e.g., by a factor of 1000 if the energy of a 10 keV electron is radiated away by 10 eV photons), each electron can experience many Compton scattering events, even though each photon scatters once at most, thus keeping the soft spectrum largely unchanged (i.e., no hard inverse Compton component). Since the density of a cooling-flow plasma rapidly increases toward lower temperatures, the optically thin region of the boundary layer is predominantly Compton-cooled at high temperatures and predominantly Bremsstrahlung-cooled at low temperatures. The observed soft-to-hard X-ray luminosity ratio for SS Cyg in outburst is $\sim 40$ (Wheatley et al. 2003), which makes it plausible that the optically thin part of the boundary layer is partly Compton-cooled, since the two emitting regions lie close to each other within the boundary layer.

To interpret the X-ray transitions, we must consider the disk instability model in more detail. The instability is principally a local property of the disk. However, once a transition from the quiescent state to the outburst state happens in one part of the disk, this propagates in the form of a heating front, behind which the mass inflow rate becomes much higher. X-ray behaviors are altered when the heating front reaches the inner edge of the disk. The optical flux, on the other hand, predominantly arises from the outer parts of the disk, which have the most emitting area. It is likely that the outburst can start at a variety of radial distances from the white dwarf in different systems or in different outbursts, and this is described as “outside-in” and “inside-out” outbursts in the studies of UV delay (see, e.g., Cannizzo et al. 1986). It is therefore possible to have a range of X-ray delay times among systems and among different outbursts for a single dwarf nova. On the return to quiescence, the cooling front is likely to start from near the outer edge of the disk, and so X-ray transition happens when it reaches the boundary layer, near the end of optical decline.

From our own analysis and a survey of the literature, we conclude that the temporary enhancement of X-ray flux during the rise and late decline has only been definitively seen in SS Cyg so far. There have only been two studies that attempt to incorporate the observational constraints imposed by the X-ray observations of dwarf novae throughout the course of an outburst into the disk instability model: the calculations of Schreiber et al. (2003) were specifically for SS Cyg, while those of Schreiber et al. (2004) were tailored for VW Hyi. These articles adopt a critical value of $M_{\text{cr}} = 10^{16}$ g s$^{-1}$ in the inner disk as the dividing line between having an optically thin or thick boundary layer, following the empirical determination by Patterson & Raymond (1985b). A comparison of the theoretical X-ray fluxes shown in Fig. 4 of Schreiber et al. (2003) with those of Fig. 9 of Schreiber et al. (2004) shows the X-ray enhancements, both during rise and decline, to be common to both models. Thus, the model can account for the behavior exhibited by SS Cyg (see Fig. 2 of Wheatley et al. 2003), but not those of SU UMa, VW Hyi, or WW Ceti (Table 1).

To investigate this further, we have derived the critical accretion rate observationally for the six systems listed in Table 1. We assume that the highest luminosity observed for the optically thin component reflects (or is close to) this critical value. We
have collected the information in Table 2, including the adopted values and references for the distances and the white dwarf mass. We convert the bolometric X-ray luminosity to accretion rate using $L = GM_1m_2/2R$, for a range of plausible values of $M_1$. We also plot the results in Figure 3 against $M_1$. For five systems, the plots are limited to the range of $M_1$ inferred from the reference cited. For SU UMa, we show three parallel lines over the entire mass range of the figure, as there are no published estimates for $M_1$. The objects are color-coded based on the presence or otherwise of hard X-ray suppression and temporary rise. For comparison, we also plot the theoretical curves from Figure 8(a) of Popham & Narayan (1995).

Unfortunately, we are unable to reach a firm conclusion, except that the observationally derived values are all much lower than what Popham & Narayan (1995) predicted. This may not be a huge problem, since the specific values depend on the assumptions made in the study, including the adopted value for the viscosity parameter, $\alpha$. The authors themselves caution against adopting these precise theoretical values, although the strong dependence on $M_1$ is likely to be a more robust conclusion. The values we derived observationally are in closer agreement with the empirical conclusion of Patterson & Raymond (1985b).

Nevertheless, we propose that the diversity of behavior shown by these six dwarf novae reflects the fact that $M_{\text{crit}}$ is in fact a function of various system parameters and not uniform among all dwarf novae. In this view, the quiescent accretion rate is already close to this value in some systems, in which case any increase during outburst will immediately lead to the development of an optically thick boundary layer and hard X-ray suppression. Moreover, we propose that the primary mass is likely to be a key parameter, partly because the conversion from luminosity to accretion rate depends on $M_1$ and partly because the theoretical investigation by Popham & Narayan (1995) indicates that the critical rate depends steeply on $M_1$.

Looking at individual systems, the inferred critical accretion rate for VW Hyi is extremely low, compared with those for other systems and with theoretical expectations. We note, however, that the distance estimate for this system relies on an indirect argument without any indication of the size of the error bar and should be refined. As for the two systems that do not show X-ray suppression during outburst, GW Lib can be understood as being due to the extremely low accretion rate in quiescence (Hilton et al. 2007). Interestingly, the inferred accretion rate for U Gem is also low. If the current mass estimate is reliable, it also has the most massive white dwarf of the six systems, which suggests that the critical accretion rate is also highest. However, both of these systems are reported to have developed an optically thick boundary layer, so the lack of hard X-ray suppression is a puzzle, particularly in light of our Compton-cooling interpretation for systems that do show hard X-ray suppression.

We believe that we should no longer assume a single critical accretion rate for all dwarf novae. Rather, we propose that future efforts be focused on determining which system parameters determine the critical accretion rate. Specifically, X-ray observations of more dwarf novae with well-determined distances and white dwarf masses should be obtained through outburst cycles. In particular, systems with extreme masses should be high-priority targets, given the likely steep dependence of the critical accretion rate on the white dwarf mass.

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