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DOI

[10.1086/316340](https://doi.org/10.1086/316340)

Publication date

1999

Published in

Publications of the Astronomical Society of the Pacific

[Link to publication](#)

Citation for published version (APA):

Howell, S. B., Ciardi, D. R., Szkody, P., van Paradijs, J. A., Kuulkers, E., Cash, J., Sirk, M., & Long, K. S. (1999). Multiwavelength superoutburst observations of T Leonis. *Publications of the Astronomical Society of the Pacific*, 111, 342-355. <https://doi.org/10.1086/316340>

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Multiwavelength Superoutburst Observations of T Leonis

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Received 1998 October 15; accepted 1998 December 9

ABSTRACT. We present results of simultaneous superoutburst observations in the X-ray, EUV, optical, and IR bands of the tremendous outburst amplitude dwarf novae T Leonis. Near peak luminosity, a single blackbody represents a good fit to T Leo’s observed continuum in the EUV spectral region, yielding a boundary layer temperature of 71,000–97,000 K. Inclusion of the longer wavelength observations, UV to the IR, indicates that a blackbody fit is inappropriate. A single-temperature fit to only the UV and redward data for T Leo works well but yields a much lower temperature, near 28,000 K. Using our own observations and previously obtained EUV, UV, and optical (super)outburst observations for the dwarf novae U Gem and SS Cyg, the SU UMa star VW Hyi, and the TOADs, TV Crv, BC UMa, and SW UMa, we find that in all cases, high-energy observations yield high-temperature, small emitting regions, while fits to UV and redward data produce cooler temperatures from much larger emitting regions. These results are consistent with the idea that high-energy data provide a direct measurement of the boundary layer, while the lower energy data measure a much larger, multitemperature region, likely to be dominated by the outburst heated inner accretion disk. High-energy outburst observations show that the boundary layer temperature decreases with decreasing orbital period, and UV outburst observations provide evidence for a missing or weak inner disk in the TOADs. We present a simple model of mass accretion onto the white dwarf during (super)outburst, which can account for the observed correlation between orbital period and boundary layer temperature.

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1. INTRODUCTION

Dwarf novae (DN) are interacting binaries consisting of a white dwarf (WD) primary and a low-mass red secondary star. The secondary fills its Roche lobe and transfers mass toward the primary, forming an accretion disk. DN are probably best known for their dramatic brightness change, which occurs during outburst. The cause of such a phenomenon appears to be a sudden accretion of mass onto the white dwarf surface from the accretion disk itself. Due to viscous heating of material within the disk, the temperature increases until ionization of the material (hydrogen) occurs, causing a heating front (pressure wave) to propagate inward, pushing material ahead of it and eventually onto the WD. Gravitational energy release by this material on the WD surface and subsequent heating of the inner disk cause the observed outburst luminosity.

The region near or on the WD surface, where the majority of the heating occurs, is called the boundary layer (BL) and is thought to be the major source of high-energy flux near the beginning of the outburst and for a number of days thereafter. The BL radiates as a hot blackbody and is thought to consist of an equatorial belt around the WD or possibly, through viscous spreading, to cover a larger part of the WD surface (see, e.g., Pringle & Savonije 1979; Kutter & Sparks 1989). Some of the luminosity from the heated BL irradiates the inner area of the accretion disk, heating it to a temperature that is well above its quiescent value. Observations of DN during (super)outburst provide opportunities to measure the physical properties of the BL and inner disk regions, leading to determinations of temperature, luminosity, and other physical properties. For typical outbursting DN, measured BL temperatures (using high-energy observations) yield values of about 1 to 3×10^5 K for short and long orbital period DN, respectively. Additionally, measures of the emitting area of the BL region generally show that it has a size approximately equal to or a few times that of the WD itself. The BL/inner disk emitting regions, measured at lower energies (e.g., UV wavelengths), have sizes of many tens that of the radius of the WD.

One subclass of DN, the tremendous outburst amplitude dwarf novae (TOADs; Howell & Szkody 1990; also called “WZ Sge” stars), have very large amplitude superoutbursts in the optical, 6 or more magnitudes. They all have short orbital periods (less than 2.5 hr) and show rare superoutbursts, although about one-third show occasional “normal looking” outbursts (Howell et al. 1995a; Richter 1992). The TOADs are optically much fainter at minimum light than a typical DN but become as bright optically during (super)outburst. We have been investigating the superoutbursts of TOADs in an attempt to understand the underlying physics of their accretion properties and disk behavior during both minimum and maximum light. Our program has used a multiwavelength approach, obtaining

observations from X-rays to the near-infrared (IR), attempting to formulate a complete picture of the accretion disk, accretion process, and BL physics. As in most campaigns of this type, obtaining simultaneous data across multiple wavebands of any given superoutburst has been difficult.

The first detailed discussion of TOAD properties appeared in 1995, when their minimum light and outburst states were examined (Howell, Szkody, & Cannizzo 1995b). Recent theoretical modeling of secular evolution of CVs (Howell, Rappaport, & Politano 1997; Politano, Howell, & Rappaport 1998), recent studies of photometric behaviors of TOADs (Warner 1995; Howell et al. 1996), and recent observational confirmation of TOAD properties (Patterson et al. 1996; Howell, Hauschildt, & Dhillon 1998; Ciardi et al. 1998) suggest the intriguing possibility that TOADs are the oldest, (post-period minimum) CVs containing very low-mass, degenerate secondaries. For example, the secondary star in WZ Sge has a mass of $\lesssim 0.05 M_{\odot}$ and a surface temperature of less than 1700 K (Ciardi et al. 1998).

TOADs exhibit superoutbursts that are similar to the outbursts of the soft X-ray transients (SXTs; Kuulkers et al. 1996; Kuulkers 1998), more so than the outbursts and superoutbursts of typical DN. Hameury, Lasota, & Huré (1997), Warner, Livio, & Tout (1996), Lasota (1995), Marsh (1998) and Charles (1998) have also found a number of similarities between the TOADs and the SXTs. Additionally, Spruit & Rutten (1998) and Mennickent & Arenas (1998) present observational evidence that indicates that the inner disk of WZ Sge (the prototypical TOAD) has a lower mass density than normal DN and appears to be truncated in some manner. This idea was first proposed for WZ Sge by Meyer-Hoffmeister & Meyer (1988). (See also Lasota, Hameury, & Huré 1995; Lasota, Kuulkers, & Charles 1998.)

We present below our results for the star T Leo for which we obtained simultaneous superoutburst observations in X-ray, EUV, optical, and IR wavelengths. Examination of these data, previous data for three typical DN, and previous superoutburst observations of three other TOADs leads us to the conclusion that the maximum BL temperature obtained during (super)outburst is correlated with the orbital period. To explain this effect, we suggest a simple model for the BL (super)outburst luminosity, based on the amount of accreted material. We also discuss the relevance of UV observations during (super)outburst in terms of their relation to the BL/inner disk temperature.

2. OVERVIEW OF RECENT HIGH-ENERGY BOUNDARY LAYER OBSERVATIONS

Standard accretion disk theory (Pringle 1987, 1989) states that during an outburst, the total luminosity of the boundary layer should be roughly equal to that of the accretion disk itself. Since the BL in a typical long-period dwarf nova

obtains an outburst temperature near a hundred thousand degrees kelvin, observations performed during outburst have emphasized the UV and recently the EUV, FUV, and X-ray spectral ranges. For example, recent observations in the EUV spectral range of dwarf novae in outburst have been accomplished for SS Cyg (Mauche et al. 1995), U Gem (Long et al. 1996), and VW Hyi (Mauche 1996; Huang et al. 1996). These three stars represent a set of DN with fairly well-understood outburst behavior, accretion disks, and stellar components, plus a factor of 3 difference in orbital period.

The high-energy observations of these three stars have led to amazingly dissimilar results on the properties of the (super)outburst induced boundary layer. However, the observations do provide good estimates of the BL temperature during outburst (see § 6). EUV outburst spectra, during early outburst and for wavelengths near the peak of the emitted flux, can be approximately fitted by a single-temperature blackbody, $T_{\text{eff}} \approx 1 \times 10^5$ – 2.7×10^5 K. The fitting of outburst spectra by a single-temperature blackbody model is not a new idea and has been known and performed for UV spectra of DN for years (e.g., Szkody 1982; Smak 1989, 1993).

We will examine below the possibility that high-energy superoutburst spectra of TOADs can also be fitted by a single-temperature blackbody. We will also see that observational outburst data of any DN, collected at wavelengths redward of the peak luminosity, can provide confusing information and imply temperatures that are not indicative of the BL itself.

3. MULTIWAVELENGTH SUPEROUTBURST OBSERVATIONS OF T LEONIS

For the past few years, the authors of this paper have had a number of target of opportunity (ToO) programs in place to perform multiwavelength observations of TOADs during superoutburst with the optical and UV yielding the largest data base to date (see, e.g., Howell et al. 1996; Szkody et al. 1996 and references therein). We present here new observational data collected during the 1997 February superoutburst of T Leo.

During this superoutburst, we obtained simultaneous observations with the *RXTE* and *EUVE* satellites, optical ground-based telescopes, and the UK infrared telescope (UKIRT) on Mauna Kea. The multiwavelength observations cover the total spectral range from 2–6 keV (~ 4 Å) to the *K* band (22,000 Å). Figure 1 shows the optical superoutburst light curve of T Leo with the times of our coordinated multiwavelength observations indicated.

3.1. Optical Photometry

Optical photometry was obtained by numerous observers during the superoutburst. Many of these observations

FIG. 1.—Optical superoutburst light curve of T Leo. The measurements (filled circles) and upper limits (arrows) have been collected from observations posted to *vsnet*. The additional symbols mark the temporal locations of our multiwavelength observations.

were made by amateur astronomers, and their data have been contributed to the AAVSO and *vsnet* archives. We show, in Figure 2, a sample of such data obtained and provided to us by Lasse Teist Jensen (Center for Backyard Astrophysics, Denmark). These data clearly show the tell-tale sign of a short-period dwarf novae at superoutburst, namely superhumps, which are present on both 1997 February 26 and March 3 UT.

3.2. Infrared Spectroscopy

A *K*-band spectrum of T Leo (Fig. 3) was kindly obtained at UKIRT by T. Geballe on 1997 February 22 UT and covered the spectral range from 1.8 to 2.5 μm . Terrestrial atmospheric water bands caused the data shortward of 2.1 μm to be unusable. The *K* magnitude during this 4 s exposure is estimated to be 11.4. The IR superoutburst spectrum of T Leo appears fairly similar to spectra seen in the optical for typical DN near maximum light, in that it shows no spectral line features at all, merely a rising blue continuum. Using the optical data available for this night (see Fig. 1), we find that during the dip preceding the actual start of the superoutburst (when the *K* spectrum was obtained), T Leo had a $V-K$ value of approximately -0.97 . However, at the start of the superoutburst, the $V-K$ color would have been near 0.0, consistent with previous results for outbursting DN accretion disks based on broadband *V*, *J*, and *K* photometry.

T Leo has also been observed in the *K*-band during minimum light (Dhillon 1998; Dhillon et al. 1998a) and reveals very strong emission lines (Paschen α , and Brackett γ , δ , and ϵ) and He I (2.05 μm) sitting on a weak, flat continuum. Furthermore, no indication of spectral line features from the secondary star are seen in the minimum light IR

FIG. 2.—CCD time series light curve of T Leo showing the clear presence of superhumps, indicating that this brightening of T Leo was indeed a superoutburst. See Fig. 1 for the placement of these data within the overall superoutburst light curve.

spectra (Ciardi et al. 1998). The minimum light IR spectral appearance of T Leo is typical of that seen in other TOADS as well (Dhillon 1998; Dhillon et al. 1998b; Ciardi et al. 1998).

FIG. 3.—K-band spectrum of T Leo obtained during the superoutburst. Note the rising blue continuum and the lack of spectral lines. An estimate of the error within the continuum is given by the noise level present. See Fig. 1 for the placement of these data within the overall superoutburst light curve.

3.3. X-Ray Observations

The *RXTE* PCA (Bradt, Rothschild, & Swank 1993) obtained X-ray information on five occasions during the first part of the 1997 superoutburst of T Leo. A total of 44.6 ks of X-ray data were obtained over the 5 days from 1997 February 21 to 25. Figure 1 shows the times of our five *RXTE* observations within the overall superoutburst, and Table 1 lists the midtimes and total on-source time of the five *RXTE* pointings.

The X-ray background is a large contributor when observing faint sources such as T Leo at maximum, and it is very important to obtain good background estimates in order to derive reliable source fluxes. The latest *RXTE* reduction software provides screening that eliminates times of high background so that the actual “good” times of observation are often much shorter than the total on-source time. For example, our February 22 and 23 observations contained good times of only 1.35 and 1.64 hr, respectively. The mean observed count rate during the five T Leo pointings revealed that only the second observation (i.e., February 22, the start of the superoutburst) had a count rate that was statistically above zero. The other four observations were consistent with zero counts detected, that of February 21 had PCU4 turned off and the last two point-

TABLE 1
1997 FEBRUARY *RXTE* AND *EUVE* SUPEROUTBURST OBSERVATIONS OF T LEONIS

<i>EUVE</i> Mid-Exposure (UT Day)	Duration (ks)	Count Rate	<i>RXTE</i> Mid-Exposure (UT Day)	Duration (ks)	Count Rate
21.516	51.4	0.003 ± 0.0012	21.615	16	Not detected
...	...	...	22.664	13 ^a	1.93 ± 0.29
24.231	44.7	0.007 ± 0.0012	23.671	14 ^a	Not detected
...	...	...	24.711	0.7	Not detected
...	...	...	25.596	0.9	Not detected

^a Actual “good times” of on source integration were only 1.35 and 1.64 hr, respectively. See text for details.

ings were very short. Figure 4 shows the *RXTE* light curve obtained on 1997 February 22. We note that T Leo appears to be brighter during the first satellite visit on that day and the entire pointing has a mean count rate of 1.93 ± 0.29 (per 5 PCUs, channels 0–23 covering the energy range of 2–6 keV).

The observed X-ray count rate during superoutburst is much less than that measured for T Leo during quiescence. Using the results of *ROSAT* PSPC pointed observations of T Leo during quiescence ($0.634 \text{ counts s}^{-1}$; van Teeseling et al. 1996; Richman 1996) and converting from *ROSAT* PSPC counts to XTE PCA (5 PCUs) counts (using a reasonable high-energy spectral shape of a 1.3 keV bremsstrahlung spectrum with $N_H = 2.1 \times 10^{20} \text{ cm}^{-2}$ from the model fit to T Leo presented in Richman 1996), we find that T Leo has an estimated minimum light X-ray (2–10 keV) count rate of $\sim 11 \text{ counts s}^{-1}$. Therefore, T Leo appears to emit at least 5 times less hard X-rays during superoutburst than during quiescence.

3.4. EUV Observations

T Leo was also observed during its 1997 February superoutburst by the *EUVE* satellite during two director’s discre-

FIG. 4.—X-ray light curve of T Leo during superoutburst on 1997 February 22. The error bars represent 1σ values for each point.

tionary time observations spanning 1997 February 21–27 (see Fig. 1). T Leo reached $V = 10.2$ during its initial rise to maximum optical light but then dropped in brightness (after 1.5 days) from this initial value to $V \sim 12$. During the first 51 ks *EUVE* observation, T Leo was barely detectable with the deep survey imager aboard *EUVE* (Bowyer & Malina 1991), providing an average count rate of only $0.003 \text{ counts s}^{-1}$. However, when T Leo rebrightened to near $V = 10.5$, it was observed during the second (45 ks) *EUVE* pointing with a mean level of $0.007 \text{ counts s}^{-1}$. These two EUV count rates correspond to a mean observed $100 \text{ \AA}$ flux of $5.63 \times 10^{-15} \text{ W m}^{-2} \mu\text{m}^{-1}$ (see Sirk et al. 1997). At this low DS imager count rate, however, T Leo was too faint to be detected in any of the three (80–700 $\text{\AA}$) *EUVE* spectrometers.

Using the two DS observations of T Leo during superoutburst, we obtained sufficient flux in each to allow photometric light curves to be produced. Observations obtained with the DS imager are collected through a Lexan/Boron filter, yielding a passband with a central wavelength of $91 \text{ \AA}$ and a full width zero intensity (FWZI) value of $\sim 100 \text{ \AA}$; however, the Lexan/Boron bandpass is not symmetric (Sirk et al. 1997). In Figure 5, we show the two EUV light curves obtained during superoutburst, each phased on the spectroscopic orbital period and ephemeris given by Shafter & Szkody (1984). We note that the first EUV observation, obtained when T Leo had dropped in optical brightness after its initial rise (see Fig. 1), is unmodulated but nonzero. The second EUV light curve, obtained during the rebrightening, shows about twice the flux level of the first observation and is clearly modulated on the orbital period. The higher EUV flux observed during the second pointing is consistent with an overall softer spectrum during superoutburst, as also indicated by the X-ray observations discussed above.

The modulations seen in the second EUV light curve may indicate asymmetric disk accretion onto the WD, some sort of enhanced emission due to either the gas stream or the secondary star, or possibly obscuration of the EUV emitting region by optically thick material. If this material were an enhanced hot spot area, the inclination of T Leo would

FIG. 5.—EUV light curves of T Leo phased on the spectroscopic ephemeris of Shafter & Szkody (1984), which at this epoch, has an accumulated error of 0.8 in phase. The top panel shows a constant but nonzero flux, while the bottom panel shows a clear modulation on the an binary orbital period. The error bars represent 2σ errors for each phased light curve point. See Fig. 1 for the placement of these data within the overall superoutburst light curve.

have to be high (however, no optical eclipse is seen) and the BL would have to be somewhat equatorially confined on the WD surface. Detailed interpretation of the modulations observed during the second *EUVE* visit is difficult as T Leo does not have a well-confined orbital inclination (28° – 65° ; Shafter & Szkody 1984) and the ephemeris of Shafter & Szkody, extrapolated to the current epoch, has an accumulated uncertainty of about 0.8 in phase. Thus, while clear orbital modulation is observed, any further phase related analysis is impossible.

3.5. Multiwavelength Results

In an attempt to characterize the temperature and other physical conditions within the boundary layer of T Leo at the peak of superoutburst, we have produced model fits (Fig. 6 and Tables 2, 3, and 4) to our multiwavelength observations using single-temperature blackbodies.⁵ The hard

X-ray flux observed during superoutburst is from optically thin gas and thus is not applicable to a blackbody-fitting procedure (Patterson & Raymond 1985; Done & Osborne 1997).

FIG. 6.—Blackbody model fits to the multiwavelength superoutburst data for T Leo. The filled triangle and square are the expected EUV flux based on the lowest and highest estimated ISM column to T Leo. The 28,000 K fit is based on use of the UV and redder points only. The mean observed X-ray flux is shown as the filled diamond. See text for details.

⁵ If the boundary layer is something like an equatorial belt, then one would expect to observe a range of temperatures from some maximum value down to that of near the quiescent white dwarf temperature. Our use of a single-temperature fit to the high-energy observations represents a sensible first step to a no doubt very complex problem.

TABLE 2
SUPEROUTBURST DATA USED IN TOAD MODEL FITS

Star	Superoutburst Date	Observed Wavelengths	References
T Leo ^a	1997 Feb	X-ray, EUV, UV ^b , V ^c , IR	1, 2
SW UMa	1992 Mar	UV ^d , V ^c	3
BC UMa	1994 May	UV ^e , V ^c	3
TV Crv	1991 Jun	UV ^f , V ^c	3

^a Includes nonsimultaneous UV outburst data for T Leo from Belle et al. 1998. See text for details.

^b IUE SWP 33464.

^c Mean *V* magnitude during peak of superoutburst.

^d IUE SWP 44227, LWP 22681.

^e IUE SWP 50665, LWP 28029.

^f IUE SWP 41843, LWP 20597.

REFERENCES.—(1) This work; (2) Belle et al. 1998; (3) Howell et al. 1995a

TABLE 3
SUMMARY OF TOAD BLACKBODY FITS^a

Star	UV Fit (K)	UV + <i>V</i> Fit (K)	Distance (pc)	Emitting Size ^b (R_{WD}) ^c
T Leo	84,000 ^d	28,000, 24,000 ^b	100	4, 14, 18
BC UMa	38,000	19,000	290	2, 7
TV Crv	37,500	24,500	350	6, 10
SW UMa	21,000	18,000	200	34, 45

^a The blackbody temperature fits were determined by a chi-squared minimization routine with the final answers rounded to the nearest 500 K. Errors of ± 500 –1000 K are expected.

^b Sizes calculated from UV fit, UV + *V* fit. T Leo has emitting sizes listed for EUV, UV, and UV + *V* + IR fits.

^c $R_{WD} = 0.01 R_{\odot}$

^d Except for T Leo for which we list fits for the EUV (second column) and the UV and UV + *V* + IR points (third column). The EUV temperature listed is the mean of the best fits for the minimum/maximum expected ISM column. See text for details.

TABLE 4
SUMMARY OF DWARF NOVAE BLACKBODY FITS^a

Star	UV Fit (K)	UV + <i>V</i> Fit (K)	Distance (pc)	Emitting Size (R_{WD}) ^b
SS Cyg	46,500	24,500	75	11, 29
U Gem	40,000	24,500	81	11, 23
VW Hyi	37,500	23,000	65	11, 27

^a Blackbody temperature fits were determined by a chi-squared minimization routine with the final answers rounded to the nearest 500 K. Errors of ± 500 –1000 K are expected.

^b $R_{WD} = 0.01 R_{\odot}$

The observed EUV flux for T Leo sets the lowest possible flux limit that we could expect in the absence of the interstellar medium (ISM). Fitting this flux value ($5.63 \times 10^{-15} \text{ W m}^{-2} \mu\text{m}^{-1}$) gives a best-fit blackbody temperature of about 65,000 K. A search of ISM column density estimates in the direction of T Leo yield values for N_H in the neighborhood of 1.2 to $5 \times 10^{19} \text{ cm}^{-2}$. These estimates are based almost entirely on EUV spectral observations of single white dwarfs, which are likely to be no further away than T Leo itself, thereby giving an estimate of a lower limit to the ISM column. Calculation of the optical depth for 100 Å and a column of $3 \times 10^{19} \text{ cm}^{-2}$ yields $\tau = 1.7$, a transmission through the ISM of 0.17. Using $\tau = 1.7$, we find that the corrected T Leo EUV flux would be near $3.3 \times 10^{-14} \text{ W m}^{-2} \mu\text{m}^{-1}$ (Fig. 6, *filled triangle*). If, however, we use the estimate for the column to T Leo provided by the somewhat low signal-to-noise X-ray data model fits of Richman (1996), N_H is equal to $2 \times 10^{20} \text{ cm}^{-2}$, giving an ISM transmission of only 9×10^{-4} at 100 Å. This column estimate can be taken as the likely maximum value to T Leo yielding a corrected EUV flux of $6.3 \times 10^{-12} \text{ W m}^{-2} \mu\text{m}^{-1}$ (Fig. 6, *filled square*). Using the ISM flux limits for T Leo we find best-fit blackbody temperatures of 71,500 and 96,500 K, respectively. Both of these fits indicate an emitting region size of a few times that of the WD. Inclusion of the UV, optical and IR points in the fitting produces very little change in the overall temperature values but greatly decreases the chi-square goodness of the fits. Figure 6 shows that neither of these best-fit blackbodies fit very well at all to the UV and redder data.

T Leo has not been observed in the UV during superoutburst, thus to provide UV fluxes we used a spectrum obtained during a normal outburst (Belle et al. 1998) and scaled it upward by a factor of 2, estimating the typical difference (outburst to superoutburst for short-period DN) as found by Szkody (1982). If we use three continuum points from the UV spectrum (or UV, optical, and IR fluxes), we obtain a best-fit temperature for T Leo of near 28,000 K, cooler than that determined from the EUV measurement (28,000 K compared with 84,000 K). Additionally, the calculated size of the emitting area is much larger, being nearly 10–20 times the size of the WD (see § 5).

Thus, it appears that for T Leo, UV and redward observations mainly provide information on a region that is larger and cooler than the boundary layer, probably the heated inner disk. Outburst observations at these wavelengths will provide flux values that are associated with the Rayleigh-Jeans (RJ) tail of the hotter BL blackbody curve peaking at much shorter wavelengths. If this hotter source were the dominant blackbody, data obtained at any wavelength could provide temperature information indicative of the BL. However, each contributor to the continuum flux (the BL, inner disk, etc.) will add to the RJ tail and cause it to become a confused multicomponent, nonlinear summa-

tion of some unknown number of blackbodies. We will explore this idea further in the next section.

4. ULTRAVIOLET AND OPTICAL (SUPER)OUTBURST OBSERVATIONS OF DWARF NOVAE

4.1. TOADs Observed at Superoutburst

In this section, we present a summary of previous superoutburst observations for the TOADs TV Crv, BC UMa, and SW UMa. The superoutburst observations used in this section are summarized in Table 2. None of these stars (with the exception of an *EXOSAT* observation of SW UMa) have had EUV or higher energy observations obtained during superoutburst. The V band fluxes used in the fits are from mean optical broadband photometry obtained during the superoutburst as close in time to the UV measurements described below (see Table 3 in Howell et al. 1995a). The UV data used in the fits are continuum points extracted from *IUE* spectra that were obtained slightly after maximum optical light (Howell et al. 1995a). This delay is typical of most campaigns of this type as the optical outburst is used as a trigger, and it then takes time to arrange satellite observations. For each star, we reexamined the *IUE* spectra and care was taken to avoid UV spectral line features and to ensure that the UV flux used in the fitting was representative of the continuum level.

We have fitted the superoutburst data in a consistent manner with single-temperature blackbody models, assuming that each data point has an uncertainty of 10%. The UV and V observations used here, while obtained during the same superoutburst, were not obtained at precisely the same instant due to satellite constraints, nighttime earthly observers, and the total length of possible coverage. Inspection of any DN (super)outburst light curve, reveals that quite soon after optical maximum the observed flux begins to decline, even within a given day. In addition, light curve fluctuations due to superhumps and flickering are usually present and can cause deviations of a few tenths of a magnitude. Thus, some uncertainty exists in the exact values to use for simultaneous multiwavelength comparison and this uncertainty will lead to uncertainties in the output results from any model-fitting procedures.

Figures 7, 8, and 9 present our blackbody fits for the TOADs BC UMa, SW UMa, and TV Crv, respectively. We fitted a single blackbody to the UV points only and then to the UV + V points to see if the observed BL flux is indeed likely to dominate these wavebands immediately after maximum light. A good fit to the observations by a single-temperature blackbody model would make the case that during the initial stages of the superoutburst, the boundary layer or some single-temperature region, becomes essentially the dominant component to the output flux. Addi-

FIG. 7.—Blackbody model fit to multiwavelength superoutburst data for BC UMa. The two fits are those for the UV data alone and for the UV plus V data. See text for details.

FIG. 8.—Blackbody model fits to multiwavelength superoutburst data for SW UMa. The two fits are those for the UV data alone and for the UV plus V data. See text for details.

FIG. 9.—Blackbody fits to multiwavelength superoutburst data for TV Crv. The two fits are those for the UV data alone and for the UV plus V data. See text for details.

tionally, the determined size of the emission region should approximately correspond to that of the WD if it truly measures the boundary layer. Our results are presented in Table 3.

We noted during our fitting process that the choice of which *IUE* outburst spectrum to use, which continuum points to use, and what total wavelength range was involved, can all allow rather large differences (10,000 K or more) in the best-fit blackbody. For SW UMa, we also fit the superoutburst UV data presented in Szkody, Osborne, & Hassall (1988) and find best-fit temperatures of 50,500 K (UV only) and 35,500 K (UV plus *U* band data). (We note here that we can obtain different temperatures for this outburst if we chose different UV continuum points or a different total spectral coverage to model.) These temperature estimates are hotter than those for the SW UMa superoutburst used here (21,000 K), but Howell et al. (1995a) show that the star SW UMa has at least two versions of superoutburst light curve behavior, one that peaks near $V = 9$ (such as that in Szkody, Osborne, and Hassall) and one that reaches only $V = 11$ (as is the case for the superoutburst modeled here). The ratio of the optical luminosity for these two SW UMa superoutbursts is roughly given by $T_{V=9}^4/T_{V=11}^4$, as would be expected for perfect blackbodies of equal emitting area.

We have used our single-temperature fits shown in Figures 7–9 and distance estimates acquired from the literature to determine the approximate size of the UV measured emission region during superoutburst. The calculated size of the emitting region is somewhat sensitive to the distance used and has a small dependence on the size chosen for the WD radius (we use $R_{WD} = 0.01 R_{\odot}$ in all cases), but neither of these parameters will effect our results greatly. The UV emission region sizes determined are much larger than the WD itself and larger than those derived from the EUV observations. These lower energy observations (UV and redward) only provide a majority of information on the physical state and size of the outburst heated inner disk and not the actual boundary layer itself.

4.2. Dwarf Novae during (Super)Outburst

In order to see if the above results for the TOADs are unique or if they are common to other DN as well, we obtained UV (*IUE* archive) and *V* (AAVSO archive) (super)outburst data for three well-known DN. The stars SS Cyg, U Gem, and VW Hyi were all reexamined in a consistent manner to that used above and blackbody model fits were produced. We used observations obtained near the start of outburst (as with the TOADs) and used superoutburst data for VW Hyi. The literature references and *IUE* spectra used in this work are as follows: SS Cyg (la Dous 1989, SWP 23533), U Gem (Panek & Holm 1984, SWP 10327), and VW Hyi (la Dous 1989, SWP 15952).

Results of our blackbody fits are in general agreement with those quoted in the literature and are summarized in Table 4. For the three stars here we find similar results as for the TOADs, that is, the UV determined emitting region is very large and adding in the *V* data results in a poorer overall fit with an even larger emitting area. The UV determined (super)outburst temperatures for these three stars are all much lower (60,000 to over 200,000 K) than those measured for these same three stars using EUV observations (see § 6).

Thus far we seem to be formulating a consistent picture of the results obtained during (super)outburst when single (or even multiple) temperature blackbody models are fitted to observational data. Observations at UV and lower energies do not provide direct measurements of the BL and are composed of some complex summation of blackbodies from many emitting regions each of some size and temperature. The energy distribution sampled by UV and redder wavelengths is composed of the tail of the hotter BL emission with contributions from the heated inner disk regions. High-energy measurements, i.e., those from a wavelength near or blueward of the peak luminosity, reveal a hotter, smaller emitting region, likely to be that of the BL alone.

5. A SIMPLE MODEL FOR LOWER BOUNDARY LAYER EMISSION DURING SUPEROUTBURST

In the IR, T Leo showed an outburst amplitude of only 2.6 mag (compared with nearly 6 mag in the optical), and in the EUV and X-ray regions, its spectrum appeared to soften during superoutburst. In addition, we found that during superoutburst, T Leo (and probably the three other TOADs as well) produced cooler BL temperatures with lower luminosity (L_{BL}) than those observed in other (longer period) DN. (We will see later that lower superoutburst temperatures are also measured for the TOADs, from UV observations; however, the situation within this waveband is complex.) In this section, let us explore a simple model idea that can produce a lower BL temperature and luminosity for a dwarf nova, as the orbital period decreases, while remaining consistent with outburst observations of normal DN.

We start with the following assumptions: (1) All accretion disks in CVs (and SXTs) have similar viscosity values (similar here only has to be within about a factor of 10 [see Cannizzo 1994; Lasota 1995]); (2) The accretion disks are all about the same size, i.e., they have an outer radius of approximately 0.75 times the primary object Roche lobe radius (Howell & Blanton 1993); (3) The volume of the disk is given by $\pi r^2 h$ (where r is the disk radius and h is the mean disk height); and (4) From Kepler's third law, the radius of the disk is proportional to the orbital period raised to the 2/3 power.

The assumption of approximately equal viscosity values is one of great debate, and in fact it has been suggested that

the TOAD superoutburst frequencies (1–30 yr) are directly caused by a minimum light (cold state) disk viscosity (α_{COLD}) being 100 times (or more) less than typical values (Osaki 1995; Howell et al. 1995b). This same idea was put forward for the SXTs (which have similar long interoutburst times) and in both types of systems, it was never considered very plausible and certainly nonphysical (Hawley, Gammie, & Balbus 1995a, 1995b; Hawley & Balbus 1998). Our model here makes no claim for the need of a radically different viscosity within the accretion disks of the TOADs but asserts that they have much lower mass accretion rates at minimum light. In addition, by analogy with the SXTs, we could assume within this model, that the TOADs inner disk is truncated in some manner (Spruit & Rutten 1998; Hameury et al. 1997; Warner et al. 1996; Lasota et al. 1995; Patterson 1980). However, in our initial presentation here, we do not make any such assumption.

The total mass within an accretion disk can be determined from

$$M_d = \rho \cdot \text{Vol.} \propto \dot{M} r^2 h,$$

where $\dot{M}$ is the average quiescent mass transfer rate (Frank, King, & Raine 1992). Alternately, we could use the fact that in a Shakura-Sunyaev (α) disk, the surface density (integrated over the vertical direction with azimuthal symmetry assumed) scales as $\dot{M}^{0.7} r^{-0.75}$, with $\dot{M}$ in units of 10^{16} g s^{-1} and r in units of 10^{10} cm (Frank et al. 1992). It then follows that the disk mass scales as $\dot{M}^{0.7} r^{1.25}$. We will see below that using the integrated surface density results in a slightly different result for the BL temperature, although well within the assumptions of our model. Relating the disk mass to the binary orbital period (P) leads to

$$M_d \propto \dot{M} P^{4/3} h.$$

We can eliminate the proportionality, by comparing the TOAD accretion disks to, for example, the better understood disk of SS Cyg. While seemingly very unrelated systems, we will see that a simple scaling argument works surprisingly well. The amount of material actually accreted onto the WD surface (BL) during an outburst, can be approximated by⁶

$$\frac{M_{\text{acc(SS)}}}{M_{\text{acc(TOAD)}}} \approx \frac{\dot{M}_{\text{SS}}}{\dot{M}_{\text{TOAD}}} \left(\frac{P_{\text{SS}}}{P_{\text{TOAD}}} \right)^{4/3} \frac{h_{\text{SS}}}{h_{\text{TOAD}}} \frac{\beta_{\text{SS}}}{\beta_{\text{TOAD}}}.$$

$\dot{M}$ is the quiescent mass transfer rate, P is the orbital period, h is the disk height (taken to be roughly equal in both cases),

and the β is the fraction of the total disk mass that gets accreted during the outburst.

The boundary layer luminosity, L_{BL} , is given by (Frank et al. 1992)

$$L_{\text{BL}} = \frac{\epsilon G M_{\text{WD}} \dot{M}_{\text{acc}}}{R_{\text{WD}}},$$

where the efficiency ϵ is 0.5 in the standard model and we use time-averaged mass accretion onto the WD. To estimate $\dot{M}_{\text{acc}}$ we make the assumption that the time scale for the initial rise to maximum light is similar for all types of DN. We do not make modifications to this standard relation for possible complications due to rapid rotation of the white dwarf or the geometry of the BL (an equatorial belt or an extended region). We further note that since $L_{\text{BL}} \propto T^4$, we can relate the above expression to a blackbody temperature expected for the BL.

We will take the mass of the WD to be similar in all cases discussed here. While this is unlikely to be the actual case, the assumption is valid to first order and, without knowing values for all the WD masses, it is the only avenue. Using literature values for SS Cyg and a typical TOAD, we find that $\dot{M}_{\text{SS}}/\dot{M}_{\text{TOAD}} \sim 5 \times 10^{-9}/5 \times 10^{-11} (M_{\odot} \text{ yr}^{-1})$; $P_{\text{SS}}/P_{\text{TOAD}} \sim 6.6/1.5 \text{ (hr)}$; and $\beta_{\text{SS}}/\beta_{\text{TOAD}}$ will be taken as 1.0. (If we believe the TOAD disks are truncated, this ratio would not equal 1.0.) Applying these values, the ratio of the total mass accreted during outburst, $M_{\text{acc(SS)}}/M_{\text{acc(TOAD)}}$, is about 720.

From Mauche et al. (1995), we find the outburst luminosity of SS Cyg is $7.6 \times 10^{33} \text{ ergs s}^{-1}$, and the BL temperature during outburst was determined (from EUV observations) to be 273,000 K (peak wavelength of 105 Å). Using our simple formulation above, we find an approximate value for the TOADs of $L_{\text{BL}} = 1.1 \times 10^{31} \text{ ergs s}^{-1}$ and a BL temperature of $\sim 52,700 \text{ K}$ (Table 5). This temperature value will be near 85,000 K if the scaling based on integrated surface density is used to estimate the disk mass. Boundary layer temperatures of 52,700–85,000 K have peak wavelengths in the FUV spectral region, consistent with our observations of T Leo discussed here.

To check if it is reasonable to make such simplistic global assumptions concerning the behavior of the accretion disks and the BL during outburst, we have followed the same reasoning as above and have used the SS Cyg template to see if we could correctly predict the (super)outburst values (T_{BL} , L_{BL}) of two other well-studied DN: the high-inclination system U Gem ($P_{\text{orb}} = 4.23 \text{ hr}$, $\dot{M} \sim 1 \times 10^{-9}$) and the short-period SU UMa system VW Hyi ($P_{\text{orb}} = 1.78 \text{ hr}$, $\dot{M} \sim 6 \times 10^{-10}$). Table 5 presents our results, all of which are scaled by EUV determined values for SS Cyg. Our simple model seems to perform well in providing approximate BL temperatures and relatively well for L_{BL} .

⁶ We will use the subscript “TOAD” to stand for a generic short-period TOAD.

TABLE 5
BOUNDARY LAYER MODEL OUTBURST PARAMETERS

Parameter	SS Cyg ^a	U Gem ^b	VW Hyi ^c	TOAD Model ^d
EUV Observations				
BL temperature (K).....	273,000	140,000	~100,000	...
Peak wavelength (Å).....	≤100	214	255	...
Luminosity (ergs s ⁻¹).....	7.6E33	4.0E34	7.7E32	...
Model Predictions				
BL temperature (K).....	...	157,600	100,000	70,000
Peak wavelength ^e (Å).....	...	222	289	428
Luminosity (ergs s ⁻¹).....	...	8.4E32	1.4E32	3.2E31

^a Mauche et al. 1995. SS Cyg used as zero point.

^b Long et al. 1996.

^c Mauche 1996.

^d Mean value used; see text for details.

^e Unreddened value.

values for the stars U Gem and VW Hyi during (super)outburst.

6. DISCUSSION

We have noted above that short-period dwarf novae appear to produce lower BL temperatures during (super)outburst compared with those of longer period. A simple model can account for these lower BL temperatures via the accretion of much less material onto the WD surface during (super)outburst as the orbital period becomes shorter. Application of this model using EUV observations of SS Cyg and applied to EUV observations of the stars U Gem and VW Hyi, appears to work well in terms of its predictive power. For T Leo, based on EUV observations, we find a BL temperature of ~84,000 K, a value consistent with the generic TOAD model calculated above. We note here that the determined size of the EUV emitting region for T Leo is 4 times the radius of the WD in size, which would lead to and unrealistically large BL flux at outburst. This large size is probably an overestimate due to the fact that we have only a photometric point, not a spectrum, thus we have no information about the spectral shape of the emission near 100 Å.

Figure 10 plots the EUV determined BL temperatures vs. orbital period for the four DN discussed here. The solid line represents a linear least squares fit to the data and the predicted BL temperature from our model is overplotted as the dashed line. T Leo is the shortest period and faintest DN yet observed during superoutburst by *EUVE*. In Figure 10, we have also plotted the UV determined temperatures for the stars SS Cyg, U Gem, VW Hyi, and T Leo as well as the three TOADs discussed in § 5. We note that

the UV outburst temperatures are well below those determined in the EUV and seem to be approximately constant until a sharp decrease occurs near a period of 1.5 hr, after which the UV temperature is a strong function of orbital period. T Leo fits the EUV determined BL temperature curve quite well but falls on the steep UV temperature curve. The solid line in Figure 10, related to the UV temperatures, is a linear least squares fit to the data with a break indicated at an orbital period of 1.5 hr. This abrupt change may simply be due to small number statistics of short-period systems.

Using UV or UV and redward observations alone will yield severe underestimates of the true BL temperature reached during (super)outburst as well as larger values for the size of the total emitting region. Thus, UV and redder observations alone are not representative of the true BL conditions but include the RJ tail of the BL as well as one or more (actually a continuum) of blackbodies related to the inner disk region. Thinking of the inner disk as a summation of blackbodies, one can picture the RJ tail of this sum (with a slope of $\lambda^{-2.2}$) being modulated with time and wavelength due to other blackbody curves peaking at various wavelengths and times throughout the outburst. A spectral fit to a peak in the curve (which over a small wavelength range would have a steeper slope approaching λ^{-4}) compared with a fit slightly off the peak, will provide different best-fit temperatures even from the same spectrum. This is because fitting of a blackbody in the RJ regime relies on the slope of the curve over the wavelength region used to determine its temperature.

It is interesting to note that the UV outburst temperatures for the TOADS are not only the coolest measured but drop sharply away from the others. The TOADS are systems that would be expected to have the lowest $\dot{M}$ -values

FIG. 10.—Determined BL/inner disk temperatures for the stars SS Cyg, U Gem, VW Hyi, T Leo, SW UMa, BC UMa, and TV Crv plotted against their orbital period. Filled squares are EUV determined temperatures for the BL near maximum light, and filled triangles are UV determined temperatures near maximum light. Note the large temperature difference between the two data sets and that fact that the shortest period systems appear to deviate from the rest of the UV temperatures.

and the weakest or most truncated inner accretion disks. If the UV observations truly measure the inner disk, Figure 10 may provide evidence that there is not much of an inner disk to be heated in these very short-period systems during a superoutburst.

Figure 11 presents the same temperature results as in Figure 10, but here plotted against the outburst amplitude as measured in the optical bandpass. We note a similar trend in the EUV values, here decreasing toward larger outburst amplitude. The star U Gem seems to deviate slightly from the linear trend, possibly a result of its rather

high system inclination. The UV determined temperatures appear to show little change with the possible exception of the two (shortest period) systems near $\Delta m \sim 5.7$. Table 6 lists the orbital periods and outburst amplitudes for the stars plotted in Figure 11.

7. CONCLUSION

We have presented the results of a multiwavelength superoutburst campaign for the TOAD T Leo. Our observations indicate that the temperature of the BL in T Leo during superoutburst was near 84,000 K, lower than those determined for longer period DN. Using high-energy observational data, we have shown that there is an overall decrease in the BL temperature with orbital period and these same data indicate that the flux emanates from a relatively small region, consistent with emission on or very near the WD surface. A simple model of outburst accretion can explain the observed behavior as merely a function of the total amount of accreted material impacting the WD surface during (super)outburst. Predictions of the BL temperature by this model are consistent with the observational determinations. Note that while it is already believed the rate of mass transfer ($\dot{M}$) decreases with decreasing orbital

TABLE 6
STELLAR DATA USED IN FIGURES 10 AND 11

Star	Orbital Period (hr)	Optical Outburst Amplitude (mag)
SS Cyg	6.6	3.9
U Gem	4.23	5.0
VW Hyi	1.78	4.5
BC UMa	1.52	7.4
TV Crv	1.50	7.0
T Leo	1.44	5.7
SW UMa	1.36	6.0

FIG. 11.—BL/inner disk temperatures plotted against the optical outburst amplitude of the dwarf novae. This figure shows the same seven stars as in Fig. 9 and indicates a decrease in BL temperature with increasing outburst amplitude.

period, our results here provide information on the rate of mass accreted onto the WD ($\dot{M}_{\text{acc}}$) during a (super)outburst as a function of orbital period.

There are, however, still a number of assumptions that we have used in our analysis that require further study. We have assumed that the WD in each dwarf nova possesses the same mass. We have assumed that the mass transfer rate during quiescence is uniquely determined by the orbital period. In reality, there appears to be different quiescent mass transfer rates even for systems with the same orbital period, resulting in the well-known “spread” in M_V seen in DN at any given period. We have assumed that the value of $\dot{M}_{\text{acc}}$ is approximately the same for all DN at the beginning of (super)outburst. We have assumed that the viscosity of the disk material is constant and uniform throughout the disk. For a given DN, the disk material may contain a variety of viscosity values even though none may be unrealistically low. Furthermore, the disks in the TOADs may be truncated in some manner. Each particular DN and possibly even each outburst, may operate with different effi-

ciency boundary layers and emitting region sizes. Finally, it is well-known that the observed BL temperatures are contaminated by other system components (Smak 1989, 1993) as the (super)outburst proceeds.

In order to proceed further in this study, simultaneous multiwavelength spectral observations of superoutbursts of DN including the TOADs need to be performed in order to disentangle all of the components involved. The conclusions presented here contain uncertainties due to the challenges posed by observing faint targets that require additional data, particularly spectroscopic results. Observations from the X-ray to the IR regions covering the entire (super)outburst are required to correctly evaluate the outburst mechanism. Studies of the state of the quiescent disk structures are critical as well. For the faint systems (i.e., TOADs), this type of observational program is currently a challenging effort, but the reward may be the development of a single broad theory governing the disk behavior in all DN outbursts with a possible extension to those of the SXTs.

We wish to thank Tom Geballe for providing the IR spectrum of T Leo during superoutburst, John Cannizzo for help with the *RXTE* observations, Koji Mukai for comments related to *ROSAT* and *RXTE* count rate conversions, Lasse Teist Jensen for his optical photometry of T Leo, and Bryce Roberts for his help with various details concerning the *EUVE* satellite and associated data reductions. S. B. H. particularly thanks Ron Oliverson for

his faith in T Leo. Partial support of this work was provided by NASA/XTE grant NAG5-4869 and NASA/*EUVE* grant GSFC 3386 to S. B. H. The United Kingdom Infrared Telescope is operated by the Joint Astronomy Centre on behalf of the UK Particle Physics and Astronomy Research Council. Some of the data reported here were obtained as part of the UKIRT Service Program.

REFERENCES

- Belle, K., Nguyen, Q., Fabian, D., Sion, E., & Huang, M. 1998, *PASP*, 110, 47
- Bowyer, S., & Malina, R. 1991, in *Extreme Ultraviolet Astronomy*, ed. R. F. Malina & S. Bowyer (New York: Pergamon), 397
- Bradt, H. V., Rothschild, R. E., & Swank, J. H. 1993, *A&AS*, 97, 355
- Cannizzo, J. 1994, *ApJ*, 435, 389
- Charles, P. 1998, in *ASP Conf. Ser. 137, Wild Stars in the Old West*, ed. S. Howell, E. Kuulkers, & C. Woodward (San Francisco: ASP), 220
- Ciardi, D. R., Howell, S. B., Hauschildt, P. H., & Allard, F. 1998, *ApJ*, 504, 450
- Dhillon, V. 1998, in *ASP Conf. Ser. 137, Wild Stars in the Old West*, ed. S. Howell, E. Kuulkers, & C. Woodward (San Francisco: ASP), 132
- Dhillon, V., Howell, S. B., Ciardi, D. R., Harrop-Allin, K., & Marsh, T. 1998a, *MNRAS*, in press
- Dhillon, V., Howell, S., Marsh, T., & Ciardi, D. 1998b, submitted
- Done, C., & Osborne, J. 1997, *MNRAS*, 288, 649
- Frank, J., King, A., & Raine, D. 1992, *Accretion Power in Astrophysics* (Cambridge: Cambridge Univ. Press), chap. 5
- Hameury, J.-M., Lasota, J.-P., & Huré, J.-M. 1997, *MNRAS*, 287, 937
- Hawley, J. F., & Balbus, S. A. 1998, in *ASP Conf. Ser. 137, Wild Stars in the Old West*, ed. S. Howell, E. Kuulkers, & C. Woodward (San Francisco: ASP), 273
- Hawley, J. F., Gammie, C. F., & Balbus, S. A. 1995a, *ApJ*, 440, 742
- . 1995b, *ApJ*, 464, 690
- Howell, S. B., & Blanton, S. 1993, *AJ*, 106, 311
- Howell, S. B., De Young, J. A., Mattei, J. A., Foster, G., Szkody, P., Cannizzo, J. K., Walker, G., & Fierce, R. 1996, *AJ*, 111, 2367
- Howell, S. B., Hauschildt, P., & Dhillon, V. 1998, *ApJ*, 494, L223
- Howell, S. B., Rappaport, S., & Politano, M. 1997, *MNRAS*, 287, 929
- Howell, S. B., & Szkody, P. 1990, *ApJ*, 356, 623
- Howell, S. B., Szkody, P., Sonnenborn, G., Fried, R., Mattei, J., Oliverson, R. J., Ingram, D., & Hurst, G. M. 1995a, *ApJ*, 453, 454
- Howell, S. B., Szkody, P., & Cannizzo, J. 1995b, *ApJ*, 439, 337
- Huang, M., Sion, E., Hubeny, I., Cheng, F., & Szkody, P. 1996, *ApJ*, 458, 355
- Kutter, S., & Sparks, W. 1989, *ApJ*, 340, 985
- Kuulkers, E. 1998, in *Disk Instabilities in Close Binary Systems—25 Years of the Disk-Instability Model*, ed. S. Mineshige & J. C. Wheeler (Tokyo: Universal Academy Press)
- Kuulkers, E., Howell, S. B., & van Paradijs, J. 1996, *ApJ*, 462, L87
- la Dous, C. 1989, *IUE-ULDA Access Guide No. 1*, ESA SP-1114
- Lasota, J.-P. 1995, in *Compact Stars in Binaries*, IAU Symp. 165, ed. J. van Paradijs, E. P. J. van den Heuvel & E. Kuulkers (Dordrecht: Kluwer), 43
- Lasota, J.-P., Hameury, J.-M., & Huré, J. M. 1995, *A&A*, 302, L29
- Lasota, J.-P., Kuulkers, E., & Charles, P. 1998, *MNRAS*, Submitted
- Long, K. S., Mauche, C., Raymond, J., Szkody, P., & Mattei, J. 1996, *ApJ*, 469, 841
- Marsh, T. 1998, in *ASP Conf. Ser. 137, Wild Stars in the Old West*, ed. S. Howell, E. Kuulkers, & C. Woodward (San Francisco: ASP), 236
- Mauche, C. 1996, in *Cataclysmic Variables and Related Objects*, ed. N. Evans & J. Wood (Dordrecht: Kluwer), 243
- Mauche, C., et al. 1995, *ApJ*, 446, 851
- Mennickent, R., & Arenas, J. 1998, *PASJ*, 50, 333
- Meyer-Hofmeister, E., & Meyer, F. 1988, *A&A*, 194, 135
- Osaki, Y. 1995, *PASP*, 108, 39
- Panek, R., & Holm, A. 1984, *ApJ*, 277, 700
- Patterson, J. 1980, *ApJ*, 241, 235
- Patterson, J., et al. 1996, *PASP*, 108, 748
- Patterson, J., & Raymond, J. 1985, *ApJ*, 292, 550
- Politano, M., Howell, S., & Rappaport, S. 1998, in *ASP Conf. Ser. 137, Wild Stars in the Old West*, ed. S. Howell, E. Kuulkers, & C. Woodward (San Francisco: ASP), p. 207
- Pringle, J. E. 1987, *MNRAS*, 178, 195
- . 1989, *MNRAS*, 236, 107
- Pringle, J. E., & Savonije, G. J. 1979, *MNRAS*, 187, 777
- Richman, H. 1996, *ApJ*, 462, 404
- Richter, G. A. 1992, in *ASP Conf. Ser. 29, Vina Del Mar Workshop on Cataclysmic Variable Stars*, ed. N. Vogt (San Francisco: ASP), 12
- Shafter, A., & Szkody, P. 1984, *ApJ*, 276, 305
- Sirk, M., Vallerger, J., Finley, D., Jelinsky, P., & Malina, R. 1997, *ApJS*, 110, 347
- Smak, J. 1989, *Acta Ast.*, 39, 317
- . 1993, *Acta Ast.*, 43, 101
- Spruit, H., & Rutten, R. 1998, *MNRAS*, 299, 768
- Szkody, P. 1982, *ApJ*, 261, 200
- Szkody, P., Osborne, J., & Hassall, B. 1988, *ApJ*, 328, 243
- Szkody, P., et al. 1996, *AJ*, 111, 2379
- van Teeseling, A., Beuermann, K., & Verbunt, F. 1996, *A&A*, 315, 467
- Warner, B. 1995, *Astrophys. Space Sci.*, 225, 249
- Warner, B., Livio, M., & Tout, C. 1996, *MNRAS*, 282, 735