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AN ASTROMETRIC CALIBRATION OF THE M_V-$P_{\rm orb}$ RELATIONSHIP FOR CATACLYSMIC VARIABLES BASED ON *HUBBLE SPACE TELESCOPE* FINE GUIDANCE SENSOR PARALLAXES[1,2]

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ABSTRACT

We present new, high-precision astrometric parallaxes for three cataclysmic variables: WZ Saggitae, YZ Cancri, and RU Pegasi, obtained using the Fine Guidance Sensors on the *Hubble Space Telescope*. The addition of these three parallaxes to the existing data set allows us to examine the outburst luminosities for dwarf novae spanning the orbital period range 1.36 hr $\leq P_{\rm orb} \leq$ 8.99 hr. We find that, after correcting for the orbital inclination, there is a simple linear relationship between the absolute visual magnitude at outburst and the orbital period. Such a relationship suggests that the only difference in the outbursts between long- and short-period systems is the actual physical size of their accretion disks. When we compare the rare outbursts of three intermediate polar systems (EX Hydrae, TV Columbae, and V1223 Sagittarii), and the visual high states of the nova-like variable RW Tri, four other cataclysmic variables with published *HST* parallaxes, with the new M_V-$P_{\rm orb}$ relationship derived for the dwarf novae, we find that the absolute visual magnitudes during the "outbursts" of these four systems attain the luminosity predicted for their orbital period. This suggests that these short-lived outbursts may also be steady state accretion events like the eruptions of dwarf novae.

Key words: novae, cataclysmic variables — stars: fundamental parameters

1. INTRODUCTION

Dwarf novae are a subset of the family of cataclysmic variables (CVs) that exhibit occasional outbursts with amplitudes of a few magnitudes. CVs are close binaries that have white dwarf primaries and cool secondary stars. The secondary star in a CV fills its Roche lobe and transfers matter via an accretion disk to the white dwarf primary. During quiescence matter is believed to slowly accumulate in the disk. At these times the accretion disk is optically thin and relatively cool. Eventually, with the continued accumulation of matter, the temperature at some annulus within the accretion disk climbs to the point ($T \approx 6000$ K), at which the opacity due to the ionization of hydrogen becomes nonnegligible. Because of the steep dependence of the hydrogen ionization fraction with temperature, the opacity rises sharply with increasing temperature. This generates a "heating front" that quickly progresses throughout the disk and both heats and expands it, which causes the rapid brightening that is the dwarf nova eruption (for more details see Cannizzo 1998 and references therein).

During a typical dwarf nova eruption the system brightens by several magnitudes and spends several days (or more) at visual maximum. The time between outbursts ranges from just a few days (ER UMa) to decades (WZ Sge). This enormous range is believed to arise from their widely differing mass accretion rates and the different viscosities these rates engender. In addition, there are two types of dwarf novae eruptions, named after their prototypes: SS Cyg outbursts and SU UMa events. Both types of eruptions are believed to be triggered in a similar fashion, but the SU UMa systems exhibit "superoutbursts," which are brighter and longer lived than their normal outbursts, and during which large, orbitally modulated variations are present in their light curves ("superhumps"). The exact driving mechanism for these events has not been fully identified, but it has been proposed that tidal forces caused by a resonance between the orbital period of the secondary star and the outer edge of the accretion disk push additional matter inward that prolongs the outburst (Osaki 1989; Truss, Murray, & Wynn 2001; Osaki & Meyer 2003).

Warner (1987) found that there was a fairly simple and tight relationship between the absolute magnitudes at outburst and

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[2] Based in part on observations obtained with the Apache Point Observatory 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium.

the orbital periods of dwarf novae: $M_V(\max) = 5.64-0.259P(\rm hr)$. This suggests that, at outburst, the accretion disks of all dwarf novae systems behave in a similar fashion: they must be optically thick and have similar radial temperature profiles. If not, the simple correction for the line-of-sight area used to derive the above equation would not produce consistent results. To better understand the processes involved in dwarf novae eruptions requires more precise calorimetry of their outbursts, and this requires accurate distances. We have previously shown (Harrison et al. 1999, 2000) that estimating the distances to dwarf novae using indirect techniques can be dangerous. For example, our geometric parallax for SS Cyg (157 pc) nearly doubled existing distance estimates for this object derived using the spectrophotometric properties of the secondary star (Wade 1982; Bailey 1981; Berriman, Szkody, & Capps 1985; or Warner 1987). In addition to identifying difficulties with the use of secondary stars for distance estimates, the parallax of SS Cyg has cast doubt on the ability of current accretion disk models to explain its outburst luminosity (Schreiber & Gänsicke 2002).

Clearly, parallaxes are the only way to confidently determine the distances to CVs. With accurate distances, we can compare the outburst luminosities of systems with different orbital periods. We present high-precision parallaxes obtained using the Fine Guidance Sensors (FGSs) for three more CV systems below, including two short-period systems, WZ Sge and YZ Cnc, that exhibit superoutbursts. With the new distances afforded by these parallaxes, we derive an updated M_V-$P_{\rm orb}$ relationship. In the next section we describe the data reduction process, followed in § 3 by a discussion of the individual systems, our results in § 4, and conclusions in § 5.

2. OBSERVATIONS AND DATA REDUCTION

The process for deriving a parallax for a cataclysmic variable from FGS observations has been fully described in papers by McArthur et al. (2001, 1999) and Harrison et al. (1999, 2000). Two new FGS parallaxes for the magnetic systems EX Hya and V1223 Sgr can be found in Beuermann et al. (2003a, 2003b). An FGS program consists of a series of observations of the target and a set of four or more reference stars located close to that target. Typically, three epochs of observations, each comprised of two or more individual pointings (*HST* orbits), are used to solve for the variables in the series of equations that define a parallax solution (eqs. [1]–[4] in McArthur et al. 2001). We briefly describe the data reduction process in this section.

2.1. *Spectroscopic Parallaxes of the Reference Frame*

Because the FGS observations are made with respect to a *local* reference frame, it is necessary to have reasonable estimates of the distances to the stars that comprise that reference frame to derive an *absolute* parallax. As in all our previous efforts for CVs, we have used a combination of spectroscopy and photometry to estimate spectroscopic parallaxes for the reference stars. The optical photometry of the reference frame stars for the three targets here was derived from several sources. The *UBVRI* photometry for the four reference stars in the YZ Cnc field was acquired using the optical imager SPIcam[3] on the Apache Point Observatory (APO) 3.5 m telescope. These data, along with observations of Landolt standards, were obtained on 2001 December 18 and were reduced in the normal fashion. The photometry of the reference frames for RU Peg and WZ Sge have been compiled from several sources, with the majority of the data coming from unpublished photometric sequences by A. Henden.[4] The final photometric data set and the sources of these data are listed in Table 1. Included in Table 1 is the Two Micron All Sky Survey (2MASS) *JHK* photometry of the reference stars, transformed to the homogenized system of Bessell & Brett (1988) using the transformation equations from Carpenter (2001). Typical error bars on the photometry are ±0.02 mag for the *V*-band measurements and ±0.03 mag for the optical colors. The 2MASS photometry for the reference stars has error bars of ±0.03 mag.

Optical spectroscopy of the reference frame stars, in addition to a large number of MK spectral type templates, has been obtained using the Double Imaging Spectrograph[5] on the APO 3.5 m on several occasions during 2001. We used the high-resolution grating with a $1''$ slit to deliver a dispersion of 1.6 Å pixel^{-1}. Only spectra from the blue side, covering the spectral region 4100–4750 Å, were acquired. By comparison of the spectra of the reference frame sources with those of the MK templates, we estimated spectral types for each of the reference stars. The derived spectral types for the reference stars are listed in the final column of Table 1.

By combining the spectral types of the reference frame stars with their photometry, we can derive the visual extinction to each target. Using the standard relations from Reike & Lebofsky (1985), the visual extinctions for each object were computed, and we list them in the eighth column of Table 2. With the spectral types and visual extinctions for all of the reference stars determined, we can obtain spectroscopic parallaxes. The final spectroscopic parallaxes (in milliarcseconds) are listed in the last column of Table 2. To determine these values, we have used the *Hipparcos* calibration of the absolute magnitude for main-sequence stars by Houk et al. (1997) and M_V for giant stars tabulated by Drilling & Landolt (2000). For input into the astrometric solution discussed below, we assumed error bars of $\pm25\%$ on our spectroscopic parallaxes.

2.2. *The Astrometric Solution*

As in our recent efforts for EX Hya and V1223 Sgr (Beuermann et al. 2003a, 2003b), we employed published values of the proper motions for our targets and reference frame stars to assist in our solution. The input proper motions for the reference frame stars in the three fields come from a large number of sources through searches using the VizieR[6] catalog search engine. Unfortunately, most of the reference stars in these three fields have rather low precision proper motions. We list the cataloged proper motions of the reference stars in columns (3) and (6) of Table 2. Values that have significant digits beyond the decimal point are averages of two or more measurements. The other proper motions in this table are from the USNO-B catalog (Monet et al. 2003). All of these proper motions, with their error bars, were incorporated into the reduction process. In our final astrometric solution, however, we found significant differences between our determinations of the reference star proper

[3] See http://www.apo.nmsu.edu/Instruments/SPIcam/Default.html.

[4] Available at ftp://ftp.nofs.navy.mil/pub/outgoing/aah/sequence.

[5] See http://www.apo.nmsu.edu/Instruments/DIS/Default.html.

[6] Ochsenbein, Bauer, & Marcout (2000). See http://vizier.u-strasbg.fr/cgi-bin/VizieR.

TABLE 1
PHOTOMETRIC AND SPECTROSCOPIC DATA FOR THE WZ SGE, YZ CNC, AND RU PEG REFERENCE FRAMES

Star	V	$U-B$	$B-V$	$V-R$	$V-I$	$J-H$	$H-K$	K	Spectral Type
WZ Sge.....	14.94[a]	−0.90	0.10	. . .	. . .	0.39	0.49	14.06	. . .
Ref-1..........	8.73[b]	0.11	0.16	0.07	0.13	0.12	−0.02	8.42	A4 V
Ref-2..........	13.10[b]	0.09	0.57	0.32	0.64	0.31	0.01	11.79	G0 V
Ref-3..........	14.47[b]	0.96	1.18	0.66	1.25	0.66	0.12	11.58	K0 III
Ref-4..........	14.14[b]	1.33	1.35	0.73	1.35	0.69	0.12	11.01	K2III
Ref-5..........	13.90[b]	1.38	1.35	0.80	1.51	0.83	0.13	10.40	K2.5III
YZ Cnc.....	14.94	−1.21	0.20	0.36	0.71	0.27	0.09	12.87	. . .
Ref-1..........	14.17	0.94	1.30	0.71	1.28	0.73	0.10	11.17	K2.5 III
Ref-2..........	15.00	0.32	0.78	0.47	0.81	0.38	0.09	13.24	G7.5 V
Ref-3..........	16.08	0.67	0.86	0.56	0.97	. . .	. . .	. . .	K1.5 V
Ref-4..........	11.56	2.00	1.70	0.86	1.59	0.80	0.14	7.95	K5 III
RU Peg......	12.62[a]	−0.58	0.62	. . .	. . .	0.48	0.19	10.48	. . .
Ref-1..........	8.86[b]	. . .	1.04	. . .	. . .	0.62	0.08	5.84	K2 III
Ref-2..........	12.59[c]	0.39	0.80	0.44	0.86	0.40	0.09	10.79	K0 V
Ref-2..........	12.61[d]	. . .	0.80	0.44	. . .	0.40	0.09	10.79	K0 V
Ref-2..........	12.62[b]	. . .	0.79	. . .	. . .	0.40	0.09	10.79	K0 V
Ref-3..........	13.47[b]	. . .	0.67	. . .	. . .	0.36	0.05	11.84	G7 V
Ref-4..........	14.53[d]	. . .	0.99	0.54	. . .	0.57	0.11	12.13	G5 III
Ref-4..........	14.55[b]	. . .	0.98	. . .	. . .	0.57	0.11	12.13	G5 III
Ref-5..........	14.53[b]	. . .	0.63	. . .	. . .	0.37	0.10	12.87	G2 V

[a] From Bruch & Engel 1994.
[b] From A. Henden at ftp://ftp.nofs.navy.mil/pub/outgoing/aah/sequence.
[c] From La Dous 1991.
[d] From Misselt 1996.

motions and some of these published values. A few of the proper motions were well outside the combined 3 σ error bars of the two sets of proper motions. If blindly included in the reduction process, such deviant points can add significant noise into the final plate solution. We have decided to ignore such data and rely on our own solutions for the proper motions of those stars.

With the input data set, equations (1)–(4) of McArthur et al. (1999) were simultaneously solved using GaussFit (Jefferys, Fitzpatrick, & McArthur 1987) to minimize the χ^2 values of the solution. The final parallaxes of WZ Sge, YZ Cnc, and RU Peg are listed in Table 3. The final astrometric precision on the parallaxes for the three new objects are all better than ± 0.5 mas. The result for YZ Cnc has the largest error, because of the asymmetry in the spatial distribution of its reference frame stars around the target and because we were required to include one very faint reference star as a result of the sparseness of this field (YZ Cnc Ref-3 is the faintest star

TABLE 2
POSITIONS, PROPER MOTIONS, VISUAL EXTINCTIONS, AND DERIVED SPECTROSCOPIC PARALLAXES FOR THE WZ SGE, YZ CNC, AND RU PEG REFERENCE FRAMES

		PM$_\alpha$ (mas yr^{-1})			PM$_\delta$ (mas yr^{-1})			
STAR (1)	$\alpha_{J2000.0}$ (2)	Previous (3)	FGS (4)	$\delta_{J2000.0}$ (5)	Previous (6)	FGS (7)	A_V (8)	π (mas) (9)
WZ Sge.....	20 07 36.4	+89.5 ± 16.0	+76.8 ± 0.6	+17 42 16.3	−12.0 ± 16	−17.5 ± 0.5	. . .	. . .
Ref-1..........	20 07 33.7	−6.8 ± 3.6	−6.7 ± 0.4	+17 40 00.3	−8.8 ± 1.9	−8.8 ± 0.3	0.00	3.98
Ref-2..........	20 07 45.8	. . .	+0.0 ± 0.1	+17 40 00.8	. . .	+0.0 ± 0.1	0.00	1.96
Ref-3..........	20 07 36.3	. . .	+0.0 ± 0.1	+17 41 05.7	. . .	+0.0 ± 0.1	0.52	0.22
Ref-4..........	20 07 36.8	−6 ± 4	−5.8 ± 0.7	+17 40 45.2	−6 ± 1	−5.2 ± 0.5	0.54	0.24
Ref-5..........	20 07 35.7	−66 ± 21	+0.3 ± 0.6	+17 42 17.1	+6 ± 9	+0.0 ± 0.5	0.64	0.27
YZ Cnc.....	08 10 56.6	+15.0 ± 5.3	+17.5 ± 0.9	+28 08 33.5	−53.4 ± 5.2	−51.8 ± 0.8	. . .	. . .
Ref-1..........	08 10 58.7	. . .	+0.1 ± 0.3	+28 07 21.4	. . .	−0.1 ± 0.3	0.23	0.18
Ref-2..........	08 11 11.5	. . .	−0.1 ± 0.3	+28 07 34.0	. . .	+0.1 ± 0.3	0.15	1.29
Ref-3..........	08 10 48.8	. . .	+0.2 ± 0.4	+28 05 11.3	. . .	−0.2 ± 0.4	0.15	1.16
Ref-4..........	08 10 33.0	−0.4 ± 3.7	−2.2 ± 1.0	+28 05 33.8	−0.2 ± 3.7	+3.6 ± 0.6	0.17	0.48
RU Peg......	22 14 02.6	−16.2 ± 3.0	−10.0 ± 0.8	+12 42 11.4	−7.2 ± 3.0	+3.1 ± 0.7	. . .	. . .
Ref-1..........	22 14 11.2	−6.7 ± 1.5	−6.9 ± 0.3	+12 42 16.9	−7.7 ± 1.5	−7.3 ± 0.3	0.00	2.57
Ref-2..........	22 14 02.8	+16 ± 46	−4.3 ± 0.8	+12 42 22.7	−220 ± 47	+2.1 ± 0.7	0.00	4.51
Ref-3..........	22 14 04.1	−18 ± 5	−9.1 ± 2.2	+12 45 04.4	−6 ± 1	−2.9 ± 0.8	0.00	1.96
Ref-4..........	22 13 58.3	+0 ± 1	+0.0 ± 0.2	+12 41 59.7	0 ± 1	+0.0 ± 0.2	0.39	0.22
Ref-5..........	22 14 07.8	−6 ± 1	−2.5 ± 0.7	+12 42 32.0	−20 ± 1	−23.3 ± 0.6	0.00	1.01

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

TABLE 3

Parallaxes and Other Data for Dwarf Novae with *HST* Fine Guidance Sensor Parallaxes

Object (1)	P_{orb} (hr) (2)	π (mas) (3)	ΔM_{LK} (4)	m_V(max) (5)	A_V (6)	i (deg) (7)	M_V(obs) (8)	M_V(corr) (9)
WZ Sge.....	1.361	22.97 ± 0.15	0.00	8.1 ± 0.1	0.00	76 ± 6	4.91 ± 0.17	3.70 ± 0.60
YZ Cnc	2.083	3.34 ± 0.45	−0.16	12.0 ± 0.3	0.00	38 ± 10	4.46 ± 0.42	5.05 ± 0.48
U Gem.......	4.246	9.96 ± 0.37	−0.01	9.45 ± 0.39	0.00	69 ± 2	4.44 ± 0.40	3.78 ± 0.43
SS Aur.......	4.387	5.99 ± 0.33	−0.02	10.85 ± 0.18	0.10	40 ± 7	4.62 ± 0.22	5.16 ± 0.32
SS Cyg......	6.603	6.06 ± 0.44	−0.04	8.58 ± 0.28	0.12	40 ± 8	2.33 ± 0.32	2.87 ± 0.38
RU Peg......	8.990	3.55 ± 0.26	−0.04	9.45 ± 0.2	0.00	41 ± 7	2.16 ± 0.26	2.68 ± 0.31

we have so far used as an astrometric reference star). Parallaxes with precisions better than ±0.5 mas can now be guaranteed using only six orbits of *HST* time.

To derive a final absolute magnitude from a trigonometric parallax, the Lutz-Kelker bias (Lutz & Kelker, 1973) has to be taken into account. The size of the bias is dependent on the trignometric precision and on the space density of the program object population (Hanson 1979). More rigorous corrections for the Lutz-Kelker bias exist (e.g., Smith 1987 or Oudmaijer, Groenewegen, & Schrijver 1998), but these applications depend on knowing the spread in absolute magnitudes of the program object population. Since CVs are interacting binaries that are not expected to have a *mean* absolute magnitude that is relevant from one object to the next, these more robust corrections for the Lutz-Kelker bias are difficult to apply. Therefore, we have simply assumed the parent population has an absolute magnitude at the brighter end of the range $0 < M_V < 10$, giving a space density index of $n = 3.0$ (see Hanson 1979), allowing us to derive a Lutz-Kelker correction to the absolute magnitudes for these three objects. The Lutz-Kelker correction for WZ Sge is negligible because of its large parallax and high precision. The corrections for YZ Cnc and RU Peg, however, are slightly more significant as a result of their greater distances. We have listed these corrections in column (4) of Table 3.

2.3. *A Reanalysis of the Parallaxes for U Gem, SS Aur, and SS Cyg*

The parallaxes for WZ Sge, YZ Cnc, and RU Peg just presented, and those for EX Hya and V1223 Sgr (Beuermann et al. 2003a, 2003b), were derived using an updated procedure that incorporates ground-based proper motions for the targets and their reference frames into the astrometric solution. In addition, the new reduction process includes a correction for the effect of "lateral color" (see Benedict et al. 1999) that arises because of the refractive nature of some of the optical elements within the FGS. Our earlier parallax program on U Gem, SS Aur, and SS Cyg did not incorporate these refinements. For completeness, we have gone back and reanalyzed the FGS data for these three objects in the same fashion as was done for the parallaxes just presented. The revised parallaxes for U Gem, SS Aur, and SS Cyg can be found in Table 3. In all three cases the new parallaxes are within the combined 1 σ error bars of the old values, and the errors on the revised parallaxes are smaller than before.

Of the three objects, only the parallax of SS Aur has undergone a significant revision, from $\pi = 5.22 \pm 0.65$ mas to 5.99 ± 0.33 mas. The addition of proper motions for SS Aur and its reference frame appears to have aided in "quieting" the astrometric solution. The error in the parallax for SS Cyg did not decline as much as the other two objects because of its own large proper motion and because two stars within the reference frame have sizeable parallaxes. In addition, our astrometric solution indicated that one of these two reference frame stars *also* has a significant proper motion.

3. DERIVATION OF THE ABSOLUTE VISUAL MAGNITUDES AT OUTBURST AND A NEW M_V-P_{ORB} RELATIONSHIP FOR DWARF NOVAE

Though our sample of dwarf novae with accurate parallaxes is relatively small, the high precision of the resulting distances allows us to investigate the outburst luminosities with greater confidence than could have been done previously. Determining the outburst luminosity of a CV requires us to have the mean visual magnitude at maximum and the visual extinction to the object. To derive a revised M_V-P_{orb} relationship requires knowledge of the orbital inclination and a prescription for correcting the apparent absolute magnitudes for this inclination. It remains disappointing that very few dwarf novae have adequate *photometric* V-band observations at more than one visual maximum, and we have to mainly rely on lower precision visual estimates that require a transformation to true V-band magnitudes that depend on the color of the star. In a test using AAVSO observations of SS Cyg, Stanton (1999) found that the transformation was $V = m_v - 0.21(B-V)$. Fortunately, the $B-V$ colors of dwarf novae at maximum are near zero, and this effect can be ignored. Where possible, we have reanalyzed the visual light curves of the program objects to arrive at new estimates of their mean peak visual magnitudes at outburst.

The uncertainties in the orbital inclinations are much larger. Orbital inclinations have been estimated using a variety of techniques, from the existence of eclipse-like features in their light curves (as in U Gem and WZ Sge) to those derived from modeling the infrared ellipsoidal variations of the distorted secondary star. Thus, we spend some time discussing the derivation of the data (listed in Table 3) that are required to generate a revised M_V-P_{orb} relationship.

3.1. *WZ Sge*

WZ Sge is an ultrashort-period CV that has had four observed superoutbursts: 1913, 1946, 1978, and 2001. The most recent outburst was extensively observed as a result of the fact that it occurred in late July, when WZ Sge is near opposition. Patterson et al. (2002) detail much of the photometric behavior of the 2001 outburst of WZ Sge, including voluminous time series photometry of the event, and list $V = 8.22$ as the peak brightness of the outburst. Landolt (2001) found $V = 8.21$ on JD 2,452,115.68. Mattei (2001) lists the peak magnitude of both the 1946 and 1978 outbursts as $m_v = 8.0$, while Brosch (1979) lists the maximum of the 1978 outburst as

$m_v = 7.9$. The peak photographic magnitudes of the 1913 and 1946 eruptions were $m_{pg} = 7.0$ and $m_{pg} = 7.7$, respectively (Mayall 1946). The 1913 eruption appears to have been substantially brighter than the other three events. Comparison of Mayall's photographic magnitudes for her brightest reference stars with modern values reveals $B = m_{pg} + 0.22$, and this implies maxima of $B_{1946}(\max) \approx 7.9$ and $B_{1913}(\max) \approx 7.2$. Perhaps the plates used in 1913 were somewhat more blue sensitive than those used in 1946 (Landolt found $U-B = -0.97$ when $V = 8.21$). With $B-V \approx -0.1$ at maximum, the last three eruptions are all consistent with a visual peak of $V = 8.1 \pm 0.1$. The lack of a 2200 Å feature in *IUE* spectra of WZ Sge leads to an estimate for the interstellar extinction of $A_V \leq 0.12$ mag (Fabian et al. 1980). We will assume that $A_V = 0.0$, as might be expected for a distance of only 43.5 pc.

Orbital inclination estimates for WZ Sge are in the range $70° \leq i < 83°$ (Patterson et al. 2002). These estimates are derived from eclipses of the hot spot on the accretion disk. Interestingly, in outburst, the depth of the eclipse varies on a 5 day period, becoming invisible at times. Patterson et al. model this as the precession of an eccentric disk. Obviously, orbital inclinations derived from these eclipse features are dependent on the model used to describe the hot spot and disk. In our orbital inclination correction for WZ Sge we will set $i = 76° \pm 6°$.

3.2. *YZ Cnc*

YZ Cnc is an important CV for distance determination because it lies on the bottom edge of the famous "period gap." For reasons not yet fully identified, there is a dearth of CVs with orbital periods between 2 and 3 hr. Until recently, it was believed that, near an orbital period of 3 hr, most CV secondaries have lost enough mass to enter the fully convective regime, which in turn causes the magnetic breaking angular momentum loss process to shutdown. The secondary star then returns to an equilibrium state inside its Roche lobe, and mass transfer ceases (see Howell, Nelson, & Rappaport 2001 and references therein). However, analysis of the spin-down rates of isolated main-sequence stars by Pinsonneault, Andronov, & Sills (2002) has shown that there is no abrupt change in the magnetic breaking rate throughout the mass regime where the fully convective boundary is located.

Like other SU UMa systems, YZ Cnc has superoutbursts during which it develops prominent superhumps (Patterson 1979). There are limited photometric *V*-band data of YZ Cnc during its normal outbursts. Both Patterson (1979) and van Paradijs et al. (1994) present photometry during normal outbursts, when YZ Cnc typically reaches $V = 12.0 \pm 0.1$. However, in the visual light curves compiled by the AAVSO and shown by both Patterson and van Paradijs et al. there is a large range in apparent magnitude for normal outbursts of $11.5 < m_v < 13.0$. Warner (1987) lists the mean maximum magnitude for YZ Cnc as $\langle m_V(\max)\rangle = 11.9$. During super-outbursts YZ Cnc can reach $m_V = 10.6$. For our analysis we will stick to normal outbursts to allow us to compare YZ Cnc with the systems thatdo not exhibit such events. We will set the mean outburst magnitude of the normal maxima to $\langle V(\max)\rangle = 12.0 \pm 0.3$.

The visual extinctions for all of the reference frame stars in the YZ Cnc field are low ($A_V \sim 0.15$). Given that these reference stars are more than twice as far away as YZ Cnc suggests that it should also suffer a low extinction. This is consistent with the finding by Szkody (1981) that $A_V = 0.0$, and we will use that value in our analysis. Shafter & Hessman (1988) found an orbital inclination for YZ Cnc of $i = 35°–40°$ from a radial velocity analysis. Unfortunately, this is the only inclination estimate for YZ Cnc that we are aware of, and, as Shafter & Hessman point out, several assumptions are contained within this determination, including an estimate for the mass of the secondary star. We will assume $i = 38° \pm 10°$.

3.3. *U Gem*

Given that U Gem shares dwarf novae prototype status with SS Cyg, it remains somewhat remarkable that there is not an abundance of actual *V*-band photometry of U Gem during maximum. There is an extensive visual history of U Gem, and Warner (1987) finds that the mean peak magnitude during outburst is $\langle m_V(\max)\rangle = 9.4$. This should be compared with the values in the compilations by Echevarria (1984), where $V_{\max} = 9.49$, 9.51, and Bruch & Engel (1994), where $V_{\max} = 9.8$. The AAVSO database has a large number of *V*-band CCD observations of U Gem near maximum, and the mean value from those observations is $\langle V_{\max}\rangle = 9.7 \pm 0.1$. We have analyzed the AAVSO visual magnitude database for U Gem, shown in Figure 1, and find a mean outburst magnitude of $\langle m_V(\max)\rangle = 9.45 \pm 0.39$ and will use this value. La Dous (1991) finds a significant extinction, $A_V = 0.15$, for U Gem, while Verbunt (1987) finds no evidence for such absorption. In our analysis of the reference frame (Harrison et al. 2000) we found that the mean extinction for the much more distant reference stars was $\langle A_V\rangle = 0.2$ mag. Like Warner (1987), we will assume that $A_V = 0.0$ for U Gem.

U Gem has been known as an eclipsing system since the early 1960s (Mumford 1962). In addition to these eclipses, U Gem also exhibits infrared ellipsoidal variations (Panek & Eaton 1982). Modeling *BVR* light curves of U Gem, Zhang & Robinson (1987) found $i = 69° \pm 1°$. Smak (2001) has reanalyzed the system parameters for U Gem and finds an inclination angle of $i = 69° \pm 2°$, and we adopt that value.

3.4. *SS Aur*

SS Aur has a similar orbital period to U Gem (4.387 vs. 4.246 hr), but a smaller outburst amplitude: $\Delta m_V = 4.2$ versus $\Delta m_V = 5.6$ for U Gem (Warner 1987). We have not been able to find any published *V*-band photometry of SS Aur at maximum. Warner (1987) used $m_V(\max) = 10.5$. Szkody & Mattei (1984) found a mean outburst magnitude of $\langle m_V(\max)\rangle = 10.8$. Analysis of the complete AAVSO data set for SS Aur, shown in Figure 2, finds $\langle m_V(\max)\rangle = 10.85 \pm 0.18$. We will use this value. Orbital inclination estimates for SS Aur derived from spectroscopic observations range over the interval $32° \leq i \leq 47°$ (Friend et al. 1990a). We will adopt $i = 40° \pm 7°$. All except one of the reference stars for SS Aur showed evidence for sizable extinctions, with $A_V \sim 0.3$ mag (Harrison et al. 2000). This is consistent with the value of $A_V = 0.1$ mag adopted by Warner (1987) for SS Aur and used here.

3.5. *SS Cyg*

SS Cyg has the most detailed light-curve history of any CV (Mattei et al. 1985). Bruch & Engel (1994) list the maximum as $V = 8.71$. Echevarria (1984) tabulates an extensive collection of photometry, and the brightest outburst magnitudes cluster near $V = 8.46$. Both values are below the $V = 8.2$ maximum brightness level adopted by Warner (1987). Analysis of the AAVSO visual light estimates for the period 1960 to 2003 (153,000+ magnitude estimates)

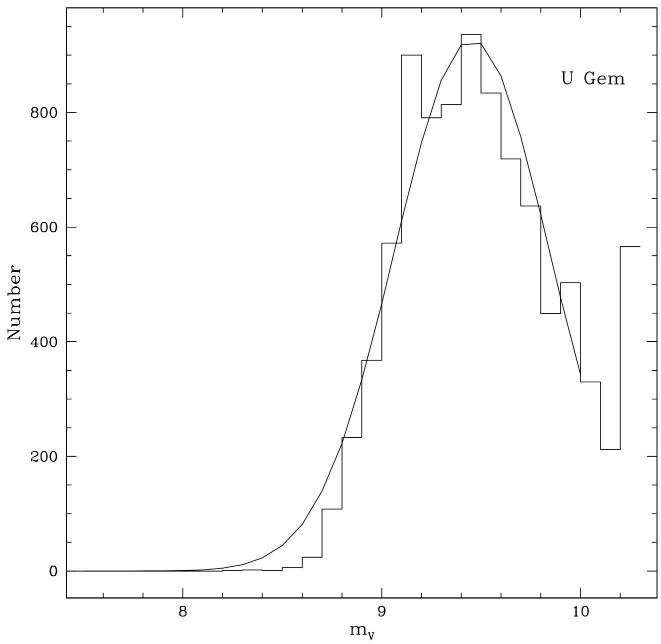

FIG. 1.—Histogram of the AAVSO data for U Gem. We have fitted a Gaussian to determine a mean visual peak magnitude of $\langle m_V(\max)\rangle$ = 9.45 ± 0.39. The AAVSO data sets for SS Aur (see Fig. 2), SS Cyg, and RU Peg were analyzed in a similar fashion.

reveals a mean peak magnitude of $\langle m_V(\max)\rangle = 8.58 \pm 0.28$. We will use this value. Verbunt (1987) estimates a color excess for SS Cyg of $E(B-V) = 0.04$, leading to $A_V = 0.12$ mag, which we will assume here.

Orbital inclination estimates for SS Cyg cover a wide range, from a value of 30° listed by Warner (1987), to an upper limit of ∼55° found by Friend et al. (1990b). Assuming the secondary is a normal K dwarf, Stover et al. (1980) and Cowley et al. (1980) found $i = 40°$, while Hessman et al. (1984) derived $i = 36°$. Friend et al. (1990b) conclude that the inclination most probably lies in the range $37° \leq i \leq 53°$. We will adopt $i = 40° \pm 8°$.

3.6. *RU Peg*

Like most of the other program dwarf novae, true *V*-band observations of RU Peg during outburst are rare. Warner (1987) adopts a peak of $m_V(\max) = 9.0$. Saw (1983) has compiled 9 yr of visual observations and found that the brightest of the 39 observed visual maxima had $m_V = 9.8$. More typically, the peak brightness was $m_V(\max) = 10.2$. Analysis of the entire AAVSO database of more than 100,000 observations reveals that RU Peg was never recorded as being brighter than $m_V(\max) = 9.2$, with a small group of outbursts having a mean value of $\langle m_V(\max)\rangle = 9.45$. We will use this latter value for RU Peg and assign it an error bar of ±0.2 mag. The visual extinction to RU Peg is very low, as indicated by the values found for the more distant astrometric reference stars. Verbunt (1987) finds $E(B-V) = 0.0 \pm 0.04$. We will assume $A_V = 0.0$ mag. Friend et al. (1990b) find that the orbital inclination for RU Peg lies in the range 34°–48°, leading to our choice of $i = 41° \pm 7°$.

3.7. *The Absolute Magnitudes of Dwarf Novae During Outburst*

Using the parameters derived above, summarized in Table 3, we can now derive the absolute visual magnitudes for the dwarf novae during outburst. In column (8) of Table 3 we list the *apparent* absolute magnitudes for these outbursts incorporating the parallaxes, the Lutz-Kelker correction, the peak visual magnitude, and the visual extinction (and the sum of the errors). To correct for the effect of orbital inclination, we utilize the same prescription as Warner (1987), following the relation from Pacyński & Schwarzenberg-Czerny (1980): $\Delta M_V = -2.5 \log [(1 + 1.5 \cos i) \cos i]$. This relation employs the *V*-band limb-darkening coefficient of $u = 0.6$ from Mayo, Wickramasinghe, & Whelan (1980), and it basically normalizes the absolute magnitude to an orbital inclination angle of 56°.7. The inclination-corrected absolute magnitudes for the six dwarf novae with astrometric parallaxes are listed in the last column of Table 3.

4. RESULTS

In Figure 3 we have plotted the corrected absolute magnitudes versus orbital period for the six dwarf novae. Ignoring WZ Sge, which only exhibits superoutbursts, a simple linear fit to these data gives $M_V = 5.92\text{-}0.383P_{\rm orb}(\rm hr)$. This relation is plotted as the solid line in Figure 3, while the updated version (Warner 1995a) of the original relation [$M_V = 5.74\text{-}0.259P_{\rm orb}(\rm hr)$] is plotted as a dashed line. The new relation is slightly steeper than the original fit as a result of the greater distances to U Gem, SS Cyg, and RU Peg found from the parallaxes. It is clear that there remains a significant amount of scatter about this relationship and that, at any orbital period, the absolute magnitude of a dwarf nova cannot currently be estimated to better than ±0.5 mag. Of the five objects, however, only SS Aur deviates significantly from the linear fit. It is odd that U Gem and SS Aur can have orbital periods that only differ by 8 minutes, yet have outbursts that differ by a factor of 3.5 in luminosity.

With large inclination angles for both U Gem and WZ Sge, and hence large corrections to their absolute magnitudes, it is relevant to explore the validity of the limb-darkening

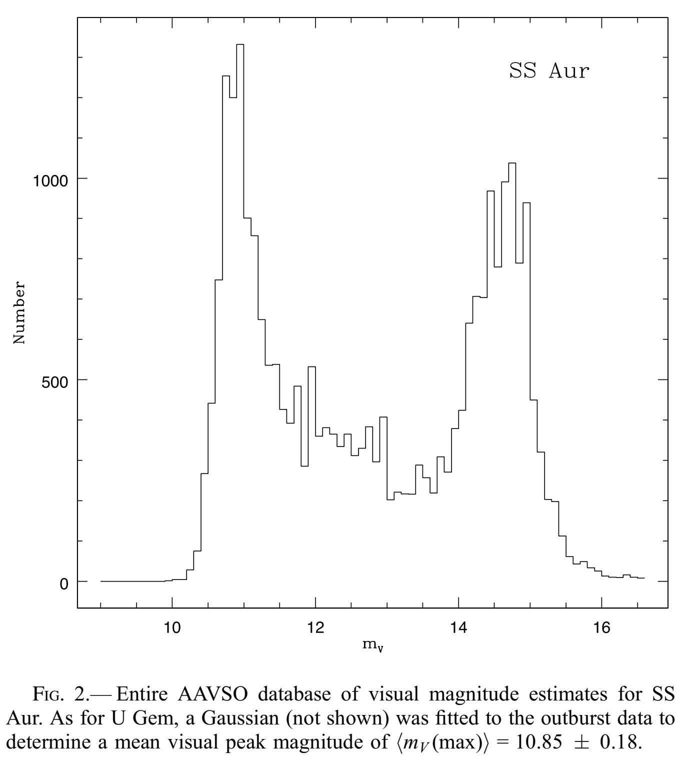

FIG. 2.— Entire AAVSO database of visual magnitude estimates for SS Aur. As for U Gem, a Gaussian (not shown) was fitted to the outburst data to determine a mean visual peak magnitude of $\langle m_V(\max)\rangle$ = 10.85 ± 0.18.

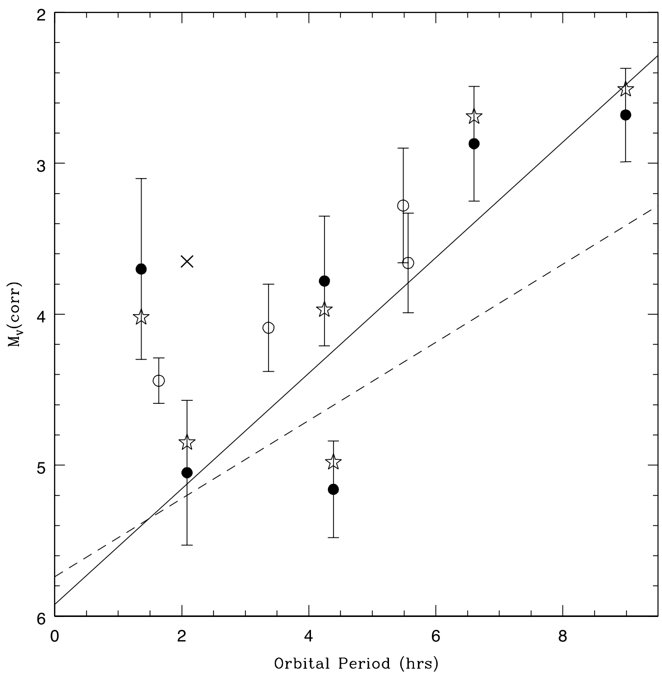

FIG. 3.— Inclination-corrected absolute visual magnitudes for the dwarf novae with *HST* FGS parallaxes (*filled circles*). The solid line is the revised M_V-P_{orb} discussed in the text for the dwarf novae. The dashed line is the old relationship from Warner (1995a). The stars are the locations of the dwarf novae if the limb darkening for the accretion disk is ignored. The single times cross is the superoutburst luminosity for YZ Cnc. We also plot the positions (*open circles*) of four other cataclysmic variables with *HST* FGS parallaxes (EX Hya, V1223 Sgr, TV Col, and RW Tri) that do not exhibit normal dwarf novae eruptions but do have rare outbursts of an unknown nature.

prescription used above and of how it actually affects our results. In Figure 3 we plot the corrected absolute visual magnitudes for our six dwarf novae without limb darkening. *Removal of the limb darkening has no effect on our result.* The rationale for inclusion of a limb-darkening effect is straightforward: optically thick accretion disks can be modeled as plane-parallel atmospheres, and tilting a disk to the line-of-sight means that the observed flux comes from higher, cooler layers in the disk's atmosphere. Diaz, Wade, & Hubeny (1996) have examined the issue of CV accretion disk limb darkening in the ultraviolet (at 1448 Å). As expected, the outer, cooler regions of the disk suffer substantial limb darkening. They found, however, that, at high mass transfer rates, the differences in limb darkening for inclinations between $1^\circ \leq i \leq 83^\circ$ were quite small over the majority of the disk, and thus an inclination-independent relationship for the limb darkening can be used. For their most luminous model, we find that the normal limb-darkening relation, $I(\theta) = I(0)(1 - u + u \cos\theta)$, with a coefficient of $u = 0.55$, works quite well. Given the difference in wavelengths and the long interval between the publications, it is a bit surprising that this value is so close to that found by Mayo et al. (1980) for the visual limb darkening. Confirmation of this fact awaits updated models for the *V*-band limb darkening of CV accretion disks.

4.1. *Comparison of the Outbursts of EX Hya, V1223 Sgr, TV Col, and RW Tri to the M_V-P_{orb} Relationship for Dwarf Novae*

There are four additional CV systems with high-precision FGS parallaxes, three intermediate polars (EX Hya, TV Col, and V1223 Sgr) and one nova-like variable (RW Tri). In their normal states the luminosity for these four systems is dominated by light from their accretion disks, and the systems exhibit small-scale variations about a mean light level. But all four systems undergo outbursts the nature of which remains unclear. For example, EX Hya spends most of its time at $m_V \sim 13.0$, but occasionally flares to $m_V \approx 9.8$ (Hellier et al. 2000). These outbursts are quite brief, usually lasting less than 2 days. TV Col is normally at $V = 14$. But several very short flares, with durations under 2 hr, have been observed in which TV Col brightens by 2 mag (Szkody & Mateo 1984; Hellier & Buckley 1993). For V1223 Sgr, only a single flare, with $\Delta m \approx 1.2$ mag, has been observed (van Amerongen & van Paradijs 1989), and the entire event lasted less than 1 day. Meanwhile, Honeycutt (2001) has discussed the "stunted" outbursts of the nova-like variables like RW Tri and has compared them with normal dwarf novae outbursts. RW Tri has small-scale outbursts on a 25 day cycle, where it brightens by 0.5 mag. Honeycutt finds that most of the phenomenology represented by normal dwarf novae outbursts is present in the stunted outbursts of the nova-like variables.

We thought it would be interesting to compare these eruptions with the relationship found for the regular dwarf novae outbursts. To do so, we have compiled the same type of data for these four objects as was used in the calibration of the dwarf nova relationship. We list these data in Table 4 and plot the inclination-corrected (with limb darkening) absolute visual magnitudes in Figure 3. It is clear that the relationship found for the outbursts of dwarf novae works quite well for the outbursts of these four systems. The result for EX Hya hints that its outbursts might be related to the superoutbursts of the SU UMa stars. It is clear that the stunted outbursts of RW Tri are quite consistent with being normal dwarf novae-type eruptions. It seems unlikely, however, that the extremely brief outbursts of TV Col and V1223 Sgr can be explained in a similar manner. While the rises to maximum of dwarf novae are very brief, less than 0.5 day, their decays take somewhat longer. With orbital periods of 3.366 and 5.486 hr, respectively, it is difficult to envision how the entire disks of V1223 Sgr and TV Col can be involved in such short-lived flares. The nature of these very short outbursts remains unclear, even though their luminosities are consistent with those of dwarf novae with similar orbital periods. Perhaps even more troubling is the single large outburst ($\Delta M = 3.5$ mag) of RW Tri observed by Still, Dhillon, & Jones (1995). The absolute magnitude of this event was $M_V \sim 0.7$, 2 mag more luminous than any of the outbursts we have so far encountered.

4.2. *Superoutbursts*

The superoutbursts of WZ Sge are amazing in that, during maximum, it is more luminous than either U Gem or SS Aur systems, which have orbital periods that are 3 times longer. Warner (1987) shows that the radius of an accretion disk (assuming its outer edge is at 70% of the Roche radius) can be found from $R_d = 1.14 \times 10^{10}(M_1/M_\odot)^{1/3}P^{2/3}$ cm, where P is in hours. Assuming similar white dwarf masses, the area of the U Gem disk is ≈4.5 times that of WZ Sge. If the radial temperature profiles of the two steady state disks were identical, then the superoutbursts of WZ Sge could never approach the outburst luminosity of U Gem without an additional source of luminosity in the system.

The luminosity of the superoutbursts of YZ Cnc (*times cross*, Fig. 3) equals those of WZ Sge. Not all superoutbursts from

TABLE 4

Parallaxes and Data for Other Cataclysmic Variables with *HST* Fine Guidance Sensor Parallaxes

Object	P_{orb} (hr)	π (mas)	ΔM_{LK}	m_V(max)	A_V	i (deg)	M_V(obs)	M_V(corr)
EX Hya ...	1.638	15.50 ± 0.29[a]	0.00	9.8 ± 0.1	0.00	77 ± 1	5.75 ± 0.11	4.45 ± 0.15
V1223 Sgr	3.366	1.95 ± 0.18[b]	−0.07	12.3 ± 0.2	0.47	21 ± 6	3.21 ± 0.28	4.09 ± 0.29
TV Col	5.486	2.70 ± 0.11[c]	−0.01	12.0 ± 0.3	0.15	70 ± 3	4.00 ± 0.31	3.28 ± 0.38
RW Tri	5.565	2.93 ± 0.33[d]	−0.12	13.0 ± 0.2	0.8	70.5 ± 1	4.41 ± 0.32	3.66 ± 0.33

[a] From Beuermann et al. 2003a.
[b] From Beuermann et al. 2003b.
[c] From McArthur et al. 2001.
[d] From McArthur et al. 1999.

SU UMa stars are equal, however, as is shown in Figure 4. Using the magnitude differences between the normal outbursts and superoutbursts of SU UMa stars from Table 3.3 of Warner (1995b), and setting the level of normal outbursts to that of our newly derived M_V-P_{orb} relationship, we find that there is at least a ±1 mag spread in the amplitude of SU UMa superoutbursts. Two systems, WX Cet and HT Cas, appear to have enormous superoutbursts whose luminosities surpass even WZ Sge and YZ Cnc. If we believe this application of the new M_V-P_{orb} relationship, the luminosity of WX Cet during its superoutbursts is larger than the eruptions of SS Cyg and RU Peg! It is essential that additional parallaxes of SU UMa systems, especially those of WX Cet and HT Cas, be obtained so as to investigate the range in outburst luminosities achieved by SU UMa systems.

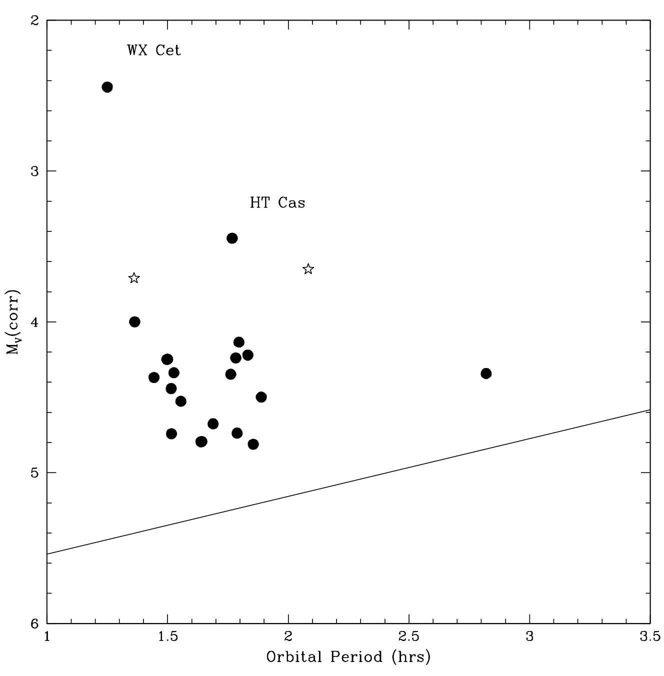

Fig. 4.—Superoutbursts of the SU UMa systems. To construct this plot, we have assumed that the normal outbursts of the SU UMa systems (listed in Warner 1995b) fall on the M_V-P_{orb} relationship derived for the dwarf novae (*solid line*). We then simply apply an offset depending on the difference in magnitude between their normal outbursts and their superoutbursts. The two stars are the locations for WZ Sge and YZ Cnc, as derived for Fig. 3.

5. CONCLUSIONS

With three additional high-precision parallaxes, we have been able to put the M_V-P_{orb} relationship for dwarf novae outbursts found by Warner (1987) on an astrometrically derived foundation. This relationship should depend on three fundamental parameters of the CV system: the masses of the two components in the binary and the mass transfer rate. Given that there is no a priori reason to expect a direct connection between any of these three quantities *and* the orbital period, it remains interesting that this relationship arises. Smak (2000) has shown, however, that this correlation is a natural consequence of accretion at the steady state mass transfer rate, and this accretion rate is really only a function of the primary mass and the orbital period. Given our small sample, it is not possible to explore how important the primary mass is in shaping this relationship.

With parallaxes for WZ Sge and YZ Cnc, we have been finally able to calorimeter superoutbursts. Such events are truly remarkable in that their luminosities approach or exceed the dwarf nova outbursts of systems with much longer periods. One possible explanation for this behavior has come from the modeling of UV spectra obtained during the normal and superoutbursts of V1159 Ori. Szkody et al. (1999) found that the outer disk annuli have higher temperatures than they do in a steady state model and that the disk during a superoutburst is hotter at all annuli compared withthe disk during a normal outburst. A similar result was found for the superoutburst of T Leonis (Howell et al. 1999). Thus the radial temperature profile of a superoutburst is different from that of a normal outburst, and all regions of the disk supply additional flux.

Our investigation of the rare outbursts from some nondwarf novae show that they might be similar to the eruptions of dwarf novae and that the accretion rate during these events appears to be near steady state. The single enormous outburst of RW Tri was as far above the ‘‘normal’’ outburst level, as those of the brightest superoutbursts of the SU UMa systems. Can long-period nova-like variables occasionally exhibit superoutbursts? Clearly, there is still much to be learned about the outbursts of cataclysmic variables, and having additional, accurate distances will be vital for further investigation.

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