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TREMENDOUS OUTBURST AMPLITUDE DWARF NOVAE

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ABSTRACT

For many years, observers have noted the existence of a number of tremendous outburst amplitude dwarf novae. We present a summary of the known observational parameters for these exceptional systems. They show outburst amplitudes of 6–10 mag, have rare outbursts (interoutburst times being months to decades), and only seem to exist in dwarf novae with short orbital periods. We calculate new accretion disk models which can reproduce their outburst behavior very well. It appears that these dwarf novae have low mass transfer rates at minimum, and the viscosity during quiescence is about 10 times smaller than for other dwarf novae. Their relation to SU UMa stars is discussed.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables

1. INTRODUCTION

Cataclysmic variables (CVs) are semidetached binary systems with orbital periods usually ranging from about 1 hr to 12 hr. They consist of a white dwarf (WD) primary and a usually less massive red dwarf secondary. Material from the secondary falls through the inner Lagrangian point and forms an accretion disk around the WD. If the WD has a sufficient magnetic field, this accretion disk can be abbreviated or nonexistent altogether. In the case of primaries with weak or no magnetic field, an accretion disk is formed which has an inner boundary at the WD surface. In one class of these accretion disk CVs, the dwarf novae (DNs), there are semiperiodic outbursts produced by either mass transfer instabilities or thermal instabilities in the accretion disk. During the high accretion outburst stage, there is a large rise in energy output from the system: the DN outburst. See Córdova (1994), la Dous (1994), and Warner (1994) for a complete review of CV properties.

The DN class of CVs can be further subdivided into systems which have orbital periods above the so-called CV period gap (~2 to 3 hr) and those which have periods below the gap. These latter systems all belong to the SU UMa subgroup (Warner 1985). The SU UMa stars show not only typical DN type outbursts (2–5 mag, lasting a few days), but less frequently (months to years) they also have superoutbursts (slightly brighter and lasting 2–3 weeks), during which time superhumps are apparent at a period a few percent longer than the orbital period. The cause of the superoutbursts is a matter of current debate (Smak 1991).

Owing to their intrinsic importance to our understanding of binary star evolution and as natural laboratories for the study of the entire accretion process, CVs have been studied in much detail in many wavelength bands. Properties such as their orbital period distribution, the component masses, the physics of the boundary layer, and the space density of such objects have been compiled. However, this type of work has mainly been carried out only for the brightest systems, such as SS Cyg and U Gem. These well studied systems are also generally close by in space, so the volume of space sampled is small.

In part to alleviate this biasing and in order to derive a better understanding of a typical CV, Howell & Szkody (1990) began an ongoing 5 yr study of faint CVs. This work has led to a somewhat different picture of CVs than previously believed (Szkody & Howell 1992, 1993; Howell 1993; Howell et al. 1993). The volume of space which Howell and Szkody surveyed (albeit incompletely) was fairly large, as the brightest apparent magnitudes were $V = 16$, and went as faint as 21st magnitude (basically the limit of historic photographic exposures). Most original sample members were at Galactic latitudes of greater than ±45 degrees. Some additional lower latitude systems were added from the literature if their apparent minimum magnitude was faint enough to make them farther away than a scale height of 150 pc (Patterson 1984). The purpose of this paper is to discuss a number of systems which show outburst amplitudes greater than the typical 2–5 mag usually seen in DNs (Warner 1994). We will attempt here to understand these tremendous outburst amplitude dwarf novae (TOADs) and how these large amplitudes are related to disk accretion and short-period binaries. This group of stars is important to our understanding of the true space density and evolution of CVs.

2. OBSERVATIONAL EVIDENCE AND DISCUSSION

Howell & Szkody (1990) presented the initial results from the high Galactic latitude CV study. Since that time, we have continued to study these stars as well as other faint CVs at low Galactic latitudes and have added considerable observational data and further insight into the nature of the original survey (see Tables 1A and 1B for revisions and additions to the original list) and the TOADs (Howell 1993; Howell et al. 1993; Szkody & Howell 1992, 1993; Howell & Szkody 1992; Howell & Hurst 1994).

Although we originally thought that the faint CVs at such high Galactic latitudes would be at distances placing them in the old disk or halo population of stars, we now have evidence

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TABLE 1A

CORRECTIONS AND REVISIONS TO THE HOWELL & SZKODY (1990) HIGH GALACTIC LATITUDE LIST

Star	Type	Comments	Reference
EG Aqr	K star	Spectroscopic identification of candidate	1, 2
CV Aqr........	DN	No candidate object found down to ≈20	3, 4
CI Aqr.........	Red star	Not a CV or wrong identification in Duerbeck	1. 2
XX Cet	QSO	...	5
AL Com.......	AM/DN	P(orb) = 84 minutes, two-pole accretion at times?	6, 7
CP Eri.........	DD	P(orb) = 28 minutes	7, 8
V360 Her......	G star	Duerbeck candidate, nova never existed	1, 9
RW UMi......	DN/N?	P(orb) = ~2 or ~4 hr	8
US 3215.......	Galaxy	Seyfert 1	5

TABLE 1B

ADDITIONS TO HOWELL & SZKODY (1990) HIGH-LATITUDE CATACLYSMIC VARIABLES

Star	Type	Minimum	Maximum	Δ	Comments	Reference
TV Crv	DN	19.5	12.5	7	=Tombaugh CV	10
2006−17	DN	16.8	21.5	4.7	...	4
HV Vir	DN	19.1	11	8	=N Vir 1929	11, 12
DV Dra	DN	>21:	15	5	...	13
RE 1149+28......	AM	...	17	...	*ROSAT* source	14
RE 1307+53......	AM	...	17	...	*ROSAT* source	15
TT Crt............	DN	16.3	12.7	3.6	=FSV 1132−11	16
CBS 132...........	DN	14	19	5	...	17

REFERENCES.—(1) Szkody & Howell 1992; (2) Duerbeck 1987; (3) Vogt & Bateson 1982; (4) Howell, unpublished; (5) Howell & Usher 1993; (6) Howell & Szkody 1992; (7) Abbott et al. 1992; (8) Howell et al. 1991; (9) Webbink 1993; (10) Levy et al. 1990; (11) Ingram & Szkody 1992; (12) Leibowitz et al. 1994; (13) Wenzel 1991; (14) Mittaz et al. 1992; (15) Osborne et al. 1994; (16) Szkody et al. 1992; (17) Wagner et al. 1988.

that this is not always the case. The original assessment was based on assigning to each star an average absolute magnitude for its class based on typical values believed at the time. (M_v = 7.5 for DNs and = 4.5 for novae and novalikes; see Wade & Ward 1985.) Further observational work by Szkody & Howell (1992 and references therein) and Sproats, Howell, & Mason (1994) has provided distances and absolute magnitudes for some of these CVs, and it is now clear that the high-latitude survey actually represents a mixture of objects of different distances and intrinsic brightness (normal and faint).

The original work (Howell & Szkody 1990) also showed what appeared to be a percentage increase in systems with short orbital periods compared with previous compilations. This may be real, or it may be a statistical result of the observational techniques used to determine the orbital periods. The period searches were generally made from data sets of length $\lesssim$4 hr. However, Shafter (1993) has shown that even among the typical brighter CVs, there appears to be a dearth of DNs between 3–4 hr. If these short-period CVs are older, as it is believed that the late stages of CV evolution do indeed cause systems to move to shorter orbital periods (see recent work by Kolb 1993; Stehle, Kolb, & Ritter 1993, 1994), we might expect large numbers of short-period systems to exist, as the observations indicate. A study aimed at looking for longer (5–8 hr) orbital periods among the faint CVs would resolve this question.

In the sample of approximately 100 high-latitude CVs, Howell & Szkody (1990) studied 56 DN of which 15 had outburst amplitudes of 6 or more mag (comparable to recurrent and some classical novae). Of these original 15, 11 now have known orbital or superhump periods (Howell et al. 1993; Leibowitz et al. 1994; Howell & Hurst 1994; Howell et al. 1991 and references therein; Ritter & Kolb 1994). We originally thought that being a TOAD might be some property peculiar to high-latitude systems (possibly related to metallicity effects), but we have now also begun a survey of low latitudes ($\leq \pm 25°$) and have discovered that TOADs are apparently at all Galactic latitudes. Ten low Galactic latitude TOADs have been identified and are included in this work (plus four more candidates), and of these, six have known orbital periods.

The determination of where to draw the cutoff in calling a system "large amplitude" is not completely straightforward. Since DNs are generally listed as having outbursts of 2–5 mag, while novae are 7–16 (with recurrent novae generally in the 7–9 mag range), we decided to place the limit of large amplitude at 6 mag. In addition, there is the problem of how to correct the observed amplitudes for inclination and other disk effects. Warner (1987) has pointed out that disks at high inclination are not as bright as those at low inclination, and he gives details for a correction function. Smak (1994) has modeled accretion disks and included their finite geometric thickness. His conclusion for high mass transfer rate ($\dot{M}_T$) (10^{17}–10^{19} g s^{-1}) systems (novae and novalikes above the period gap) is that for high inclinations there can be a large correction factor needed in M_v, basically still in agreement with the results of Warner. However, for accretion rates of 10^{16} g s^{-1} or less (see § 3), nonstationary accretion will occur and the inclination angle may have little effect on M_v determinations except for inclinations ≈90°. In this case, the geometric thickness of the accretion disk (h/r) will be much smaller, but this simple picture is complicated by the fact that these weak disks are likely to be optically thin. The result of these factors is that the observed amplitude range for a high inclination, geometrically and optically thin disk (with no correction needed at

TABLE 2

TOADs (≥6.0 mag) WITH KNOWN ORBITAL PERIODS

Star	Recurrence Time of Superoutburst (days)	Orbital Period (minutes)	Outburst Amplitude (mag)	Galactic Latitude
WX Cet	3600	81[a]	8.5	−79
WZ Sge........	11000	81.6	7.5	−8
SW UMa......	400	81.8	7.3	+37
LL And	5000	82.2[a]	6.0	−36
HV Vir	3600	83.5	7.6	+64
AL Com.......	Decades?	84?	9.0	+76
VY Aqr........	600	91	8.5	−35
BC UMa	...	91.2	7.4	+65
UV Per	...	93.3[a]	6.5	−4
GO Com	...	94.8	6.9	+88
BZ UMa	180	97.8	7.3	+39
RZ Leo	...	102	7.7	+59
KV And	...	104[a]	7.9	−19
AY Lyr	270	105.7[a]	6.1	+17
TT Boo	...	108[a]	6.9	+60
KK Tel	...	112	6.2	−36
TV Crv	...	120.[b]	7.0	+42
EF Peg	200	123[a]	7.9	−23
AR And	...	236	6.6	−23
WW Cet.......	...	253.2	6.4	−71

[a] Superhump period.

[b] B. Warner (private communication) has observed superhumps with a period near 2 hr.

quiescence), may be much less than the real amplitude as corrections are applied to the optically thick disk at outburst. Given that these corrections are not well determined, however, we decided it was best to deal only with systems that are observed to have large amplitudes at the current time.

For the 19 TOADs with known orbital periods (see Table 2), *all* are below the period gap (orbital periods of 2.1 hr or less), with the caveat that the period of AR And is above the gap (Shafter, Veal, & Robinson 1995), and it is not clear if WW Cet is a normal type of dwarf nova or some sort of novalike system (Warner 1987). Figure 1 shows a plot of the outburst amplitude for each TOAD with a known orbital period. Different symbols are plotted for the high and low Galactic latitude TOADs. We see no apparent differences between the two latitude groups, but there appears to be a trend toward larger outburst amplitude with shorter orbital period. We are still well within the regime of small number statistics, however.

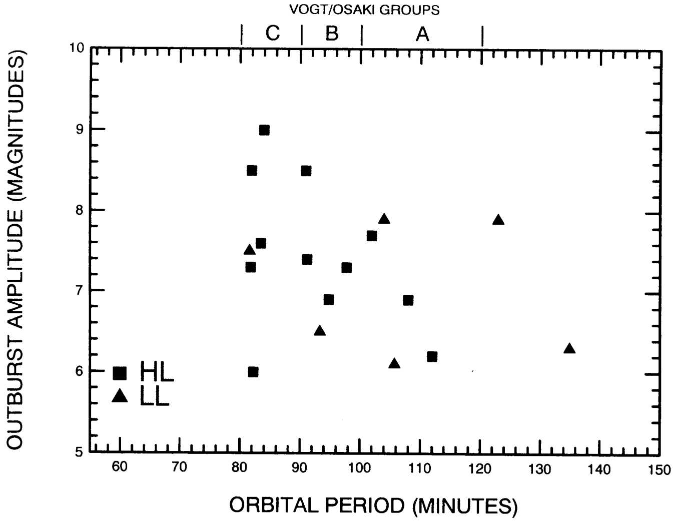

FIG. 1.—TOADs with known orbital periods. HL denotes high latitude, and LL denotes low latitude TOADs. AR And and WW Cet are not plotted. See Table 2.

TABLE 3

TOADs WITH UNKNOWN ORBITAL PERIODS

Star	Outburst Amplitude (mag)
GW Lib	9.5
UZ Boo	9.0
V592 Her..............	>7.2
AO Oct.................	7.5
V551 Sgr	6.5
FQ Sco	6.5
AK Cnc	6.2

Table 3 lists confirmed TOADs (classified by their outburst amplitude) which have no known orbital period. Table 4 poses a challenge for observers by listing candidate TOADs which have essentially no information concerning their true minimum magnitudes but are likely to be TOADs. The amplitudes in Table 4 are mostly based on the General Catalogue of Variable Stars (GCVS) (Kukarkin 1969) minimum magnitudes, which are given as "fainter than." So far, we have only made a detailed search of the GCVS for TOADs in two Galactic latitude bins; approximately ≥ ±40°–45° and approximately ≤ ±25°. We have no doubt that more TOADs and candidates are out there waiting to be found.

Determining distances for these stars has been a slow process associated with fairly large uncertainties. From the few we have determined and those which existed in the literature, we find that the TOADs are at a variety of distances; $\lesssim 100$ pc to $\gtrsim 500$ pc (Bailey 1979; Szkody & Howell 1992; Sproats et al. 1994). Translating the apparent magnitudes and distances into absolute magnitudes is complicated owing to the inclination problems noted earlier. Table 5 shows the distances determined for the TOADs. Inclination effects can be quite large and certainly are important. Warner (1987) gives details for a correction function based on some well observed systems. He derives a relation between absolute magnitude and orbital period which results in mean values of absolute magnitude between 9.3–9.1 for systems with orbital periods between 81 and 123 minutes. Only WZ Sge has a known inclination, so that the absolute magnitude can be corrected for this effect. For the others, the inclination is less than 70°, so the correction factor for the listed values will be ≤1 mag at most. Of the eight systems with known distances, half have M_v's close to a normal value of 9, while BC UMa, AK Cnc, AL Com, and BZ UMa are at least 1 mag fainter. Much more work is needed in the area of absolute magnitude determination both from observational distance determinations and from theoretical modeling

TABLE 4

TOAD CANDIDATES WITHOUT KNOWN MINIMUM MAGNITUDE

Star	Likely Outburst Amplitude
DV Dra	>6.0
FV Ara........	>6.0
QY Per	>5.8
V336 Per	>5.7
HW Tau.......	>5.5
V421 Tau......	>5.5

TABLE 5

TOADs WITH DISTANCE AND M_v MEASUREMENTS

Star	d (pc)	M_v[a]	Reference
WZ Sge	90	10.7 (9.5)[b]	1
BC UMa	130–400	11.0–13.5	2
AK Cnc	210–420	10.4–11.9	3
WW Cet	130	$\lesssim$9.4–12	4
AL Com	$\geq$190	13.50	6
RZ Leo	$\geq$210	$\gtrsim$9–12	6
GO Com	$\geq$525	10.1	6
BZ UMa	110	12.6	7

[a] Warner (1987) gives $M_v = 9.1$–9.3 for normal short-period DNs.

[b] The value in parentheses is corrected for an inclination of 76°.

REFERENCES.—(1) Krzeminski & Smak 1971; (2) Mukai et al. 1990; (3) Szkody & Howell 1992; (4) Patterson 1984; (5) Young & Schneider 1981; (6) Sproats, Howell, & Mason 1994; (7) Ringwald 1993.

of the accretion process and disk structures at low mass transfer rates.

Support for the idea of large numbers of CVs that are fainter than previously thought comes from the work of Shara et al. (1993). They found 13 faint CVs in 2 square degrees, all near $B = 19.2$. A nearby "control" region showed three in 0.5 square degrees confirming that the first region was not odd in some respect. The candidates show Balmer emission lines (indicating that they are likely systems with optically thin accretion disks and with low mass transfer rates), and four that have been photometrically monitored show typical DN minimum light curves. They conclude that these objects must be rather close by (due to their blue color) and, if so, would lead to a space density of about 10^{-4} pc^3, approximately 100 times that derived from a number of large area surveys (see Patterson 1984). These larger area surveys, however, did not go to faint magnitudes (B[limit] $\sim$ 16), so they are not likely to be good indicators of the true space densities, in particular for the faint CVs.

Another aspect that emerged from our survey work concerns the stability of the quiescent magnitudes. Howell et al. (1990) compiled a list of CVs with known historic minimum magnitude variations. This list consisted of 15 stars (out of 56 with sufficient information) which showed evidence for quiescent magnitude changes of 0.7 mag or greater over timescales of months to years. Of the 11 TOADs known at that time, seven were on the list of CVs with highly variable minimum magnitudes. While the list in Howell et al. (1990) in itself is not conclusive, having been drawn from various sources and observational techniques, it may provide some incentive for us to consider at least performing an observational monitoring study of short-period CVs at minimum. Hempelmann (1993) and Cannizzo & Mattei (1992) have both presented evidence for mass transfer variations in SS Cygni (see, however, Cannizzo 1993b), and Wood (1994) has done the same for HT Cas. Livio (1993) goes even further and provides a good discussion of observations of many systems which have strong evidence for $\dot{M}_T$ fluctuations from the mean, whose magnitude changes over time are interpreted as variations in $\dot{M}_T$ for the system. Studies aimed at an understanding of the frequency and amplitude of such changes would be valuable. One such study, for longer period novalikes, is reported in Jurcevic et al. (1994) and clearly demonstrates these minimum magnitude changes. How the accretion disk is formed and behaves over time in these short-period systems is currently unknown. This minimum magnitude variation will also make the M_v determination uncertain.

The TOADs have outburst amplitudes which are comparable to recurrent novae. This makes even the ones with faint apparent magnitudes easy to study during maximum light. The problems encountered are: (1) they are generally not on any list monitored by amateurs or professionals due to their faint minimum magnitudes, (2) the outbursts (brighter than 15th magnitude) last for only a few days to a week, and (3) the (tremendous) outbursts often occur infrequently (see Howell 1991, Richter 1993, and Table 2). Photometric and spectroscopic observations of TOADs at outburst have been undertaken in the optical by Howell et al. (1993), Levy et al. (1990), Howell & Hurst (1994), Leibowitz et al. (1993), and others, and in the UV by Howell et al. (1995). These studies have revealed that at maximum light, TOADs resemble typical short-period DNs, in that all with sufficient photometric coverage show superhumps (these possibly occur in all TOADs, but there is not yet enough observational coverage), and spectroscopically they have essentially featureless continua with absorption lines appearing at maximum. At minimum, spectroscopic and photometric observations (Mukai et al. 1990; Howell et al. 1991 and references therein; Szkody & Howell 1993; Howell, Liebert, & Mason 1994a, b, c; and Howell et al. 1991 and references therein) show evidence for strong emission lines of H (and sometimes He), photometric flickering, and orbital humps, typical of DNs. These properties are usually attributed to systems which have low mass transfer rates (10^{15} g s^{-1}) and optically thin disks (Patterson 1984).

Observations are still very sparse for the TOADs, and detailed studies are difficult due to their faintness at minimum. Parameters such as the component masses, distances and M_v's, and the details of the outburst cycle are subjects of our ongoing work. Trying to tie the tremendous outbursts to some property of these systems and to develop models which account for the behavior is still in its infancy, and we discuss our initial attempts in § 3.

Vogt (1993) and Osaki (1993) have proposed that the SU UMa stars are themselves subdivided. Their idea is that the DNs are divided into three groups based on the activity of outbursts and superoutbursts. (We note here that in Osaki 1993, RZ Leo is listed in group C; however, its orbital period would place it in group B.) These groups, going from group A (active) to group C ("WZ Sge" stars) also represent a grouping by orbital period. This seems to be a natural system based on DNs progressing from longer to shorter orbital period, more to less outburst activity, and frequent to less frequent outbursts and superoutbursts. The decreasing activity with decreasing orbital period may be partially due to the general scaling of $\dot{M}_T$ with orbital period (Patterson 1984). The models in § 3 show, however, that TOAD behavior appears to need both low $\dot{M}_T$ *and* very low viscosity value. Simply lowering the value of $\dot{M}_T$ alone will not produce models that match the TOADs (see also Smak 1993; Osaki 1994).

If we place the known TOADs within this proposed scheme, however, we see that, like WZ Sge, a few of them (based on their orbital periods), lie within group C, but the TOADs are roughly equally spread out within all three groups (see Table 2 and Fig. 1), and this clearly shows that if WZ Sge is a TOAD (which we believe it is), then the group C ("WZ Sge" stars) is not a homogeneous group as proposed. For example, EF Peg should be placed in their group A by orbital period and recurrence time of superoutburst, yet it is also in group C if we use

Vogt and Osaki's criterion of delay of superhumps after outburst (Howell et al. 1993). We find that the TOADs, while having some equivalent properties, do not fit into the Vogt or Osaki subclasses.

TOADs appear to show slightly shorter superoutbursts (lasting 1–1.5 weeks [Howell et al. 1993; Howell & Hurst 1994]) than typical SU UMa systems (2–3 weeks). However, HV Vir had a superoutburst last for 50 days and WZ Sge for 126 days! These systems are apparently unusual, but the number of studied TOAD superoutbursts is very small. The TOADs appear to be all SU UMa systems (in the sense that they all show superhumps when searched and have short orbital periods) and some have *only* superoutbursts (searching the literature shows that normal outbursts and superoutbursts are evident for VY Aqr, BZ UMa, RZ Leo, WX Cet, SW UMa, and AY Lyr).

It appears that most, if not all, TOADs show superoutbursts, have low $\dot{M}_T$, and very low viscosity (see next section), while the SU UMa stars show superoutbursts at times but also have regular outbursts. Since these two types of DN have the same period distribution (i.e., short, below ~2.1 hr), maybe the two types are in fact the same systems but at different times in their evolution.

3. MODELS

In order to constrain the input parameters that are required to obtain the observed properties of the TOADs, we now present models for the outbursts of DNs relevant to this paper. The time-dependent model for the accretion disk limit cycle theory is described in Cannizzo (1993b, hereafter C93b). For a recent review of the limit cycle theory, see Cannizzo (1993a).

The basic operation of the limit cycle process involves a storage of material in the accretion disk during quiescence, followed by a dumping onto the WD primary during outburst. The disk is not in steady state in quiescence: matter accumulates at large radii. At some point the local surface density $\Sigma(r)$ somewhere in the disk surpasses a critical surface density $\Sigma(r)_{\max}$ above which heating exceeds cooling, and the gas in that annulus heats rapidly from 3000–5000 K up to ~100,000 K. The strong gradient in the viscosity between that in the heated annulus and that of the neighboring, cool disk produces a vigorous flow out of this annulus, both to smaller and larger radii. This process rapidly transforms the rest of the disk to the hot state. During the following readjustment period, the surface density distribution $\Sigma(r) \propto r^n$ shifts from a profile in which $n \sim 1$ to one in which $n \sim -\frac{3}{4}$. There are two possibilities for what can occur next. If the mass in the disk is relatively small, then the surface density at the outer disk edge is less than the critical surface density which instigates a cooling transition (often called $\Sigma_{\min}$), and so a cooling wave immediately begins to propagate inward and to shut off the flow of matter in the disk to smaller radii. If the mass in the disk is relatively large, then the surface density at the outer disk edge can exceed $\Sigma_{\min}$. The entire disk must therefore remain in the hot, totally ionized state while accretion onto the WD occurs. After the mass of the disk has been depleted by a significant amount, the surface density at the outer edge becomes smaller than $\Sigma_{\min}$, and the cooling front can begin to propagate. Because the timescale to accrete onto the WD is slower than the timescale for the cooling transition to occur, the DN outbursts for which $\Sigma(r_{\text{outer}}) < \Sigma_{\min}(r_{\text{outer}})$ at the start of the outburst have light curves which rise to maximum and immediately decay back to quiescence, and they last for just a few days; those for which $\Sigma(r_{\text{outer}}) > \Sigma_{\min}(r_{\text{outer}})$ at the start of the outburst have light curves which rise to maximum and decay slowly for about 1 week and which then decay faster. The faster decay rate is the same for both types of outbursts, consistent with the Bailey (1975) relation giving the exponential time constant as a function of orbital period (Warner 1994). The period of slow decay in the latter type of bursts, called the "viscous plateau" by C93b, corresponds to the time during which the cooling front is unable to propagate. A textbook example of a system containing these two types of outbursts is SS Cyg (C93b).

We now present some numerical attempts at reproducing a TOAD light curve. Some modifications of the code used here (see C93b) are given in Cannizzo (1994). In particular, we now allow the viscosity parameter α to vary with radius. The two primary shortcomings of models of the type described in C93b in which α is taken to vary in a step function between the low and high states of the disk are caused by the fact that the viscous timescale $(1/\alpha\Omega)(r/h)^2$ (where α is the viscosity, Ω is the Keplerian angular velocity in the disk, r is the disk radius, and h is the disk semithickness) scales with radius so that it is smallest near the inner disk edge. Because of this, (1) outbursts always start very near the inner disk edge (see also Lin, Papaloizou, & Faulkner 1985; Ludwig, Meyer-Hofmeister, & Ritter 1994), and (2) the outburst decays have a faster than exponential form (Cannizzo 1994). To correct this "problem" in the current models we take $\alpha = \alpha_0(r/r_{\text{outer}})^{\epsilon}$, where $\epsilon = 0.325$ (Cannizzo 1994). Furthermore, we take $r_{\text{outer}} = 2 \times 10^{10}$ cm and $M_{\text{WD}} = 1\ M_{\odot}$, and we use 100 radial grid points. The light curves are computed assuming Planckian flux distributions, taking a face-on disk at $d = 100$ pc.

Figure 2 shows the results of varying the secondary mass transfer rate $\dot{M}_T$ in the computations. For the five panels shown, $\alpha_{\text{cold}} = 0.001$ and $\alpha_{\text{hot}} = 0.2$. Smak (1984) showed that the Bailey relation giving the time constant for the exponential rate of decay of the DN outbursts constrains α_{hot} to be about 0.2. We have followed this paradigm by taking α_{hot} to be a "universal constant" and allowing other parameters to vary.

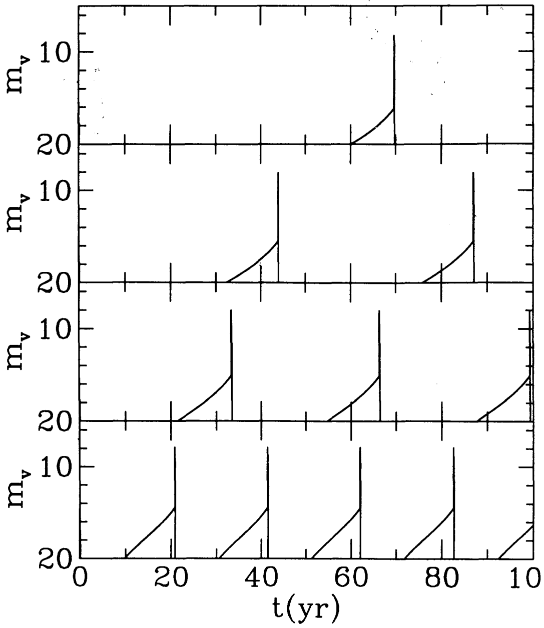

FIG. 2.—The effect of varying the mass transfer rate. For the four panels shown, $\alpha_{\text{cold}} = 0.001$, $\alpha_{\text{hot}} = 0.2$, and $\dot{M}_T/10^{15}$ g s^{-1} = 1, 2, 3, and 6 from top to bottom, respectively.

For the adopted input parameters in this study, the outbursts are all of the viscous plateau variety, that is, a significant fraction of the matter stored during quiescence must be accreted onto the WD before the cooling front can begin to propagate and shut off the outburst. This is a direct consequence of the large ratio $\alpha_{\rm hot}/\alpha_{\rm cold}$ which we must adopt in order to get the long recurrence times. This forces a significant contrast between $\Sigma_{\rm max}$ and $\Sigma_{\rm min}$. Since most of the stored matter in the disk is accreted during a superoutburst, the time to replenish the disk and build up to the next outburst depends on the rate of replenishment, i.e., $\dot{M}_T$. This is seen directly in Figure 2 by noting the decreased recurrence times as $\dot{M}_T$ is made to increase.

Figure 3 shows the effect of changing $\alpha_{\rm cold}$ in the computations. For the five panels shown, we again fix $\alpha_{\rm hot} = 0.2$, set $\dot{M}_T = 2 \times 10^{15}$ g s^{-1}, and take $\alpha_{\rm cold} = 0.001$, 0.002, 0.004, 0.006, and 0.010, respectively. The critical surface density $\Sigma_{\rm max}$ which controls the amount of matter stored in quiescence varies inversely with $\alpha_{\rm cold}$, so increasing $\alpha_{\rm cold}$ decreases the amount of matter that can be stored before $\Sigma_{\rm max}$ is exceeded and the next outburst is triggered. With $\dot{M}_T$ fixed, increasing $\alpha_{\rm cold}$ decreases the recurrence time for outbursts. Figure 4 shows an expanded view of individual outbursts from each panel of Figure 3. We see the characteristic outburst profile of the viscous plateau outbursts: an initial slow decay, followed by a more rapid decrease of the light once the cooling front is able to form at the outer disk edge and to propagate inward, thereby shutting off the flow of matter in the high state. Since the mass of the disk is decreasing as we increase $\alpha_{\rm cold}$, the amount of matter that must be lost from the disk onto the WD in order to lower the surface density at the outer edge to the point where $\Sigma(r_{\rm outer}) < \Sigma_{\rm min}(r_{\rm outer})$ becomes less, and therefore the amount of time necessary to accomplish this also decreases. This accounts for the diminishing amount of time spent on the viscous plateau of the outbursts as $\alpha_{\rm cold}$ is made to increase.

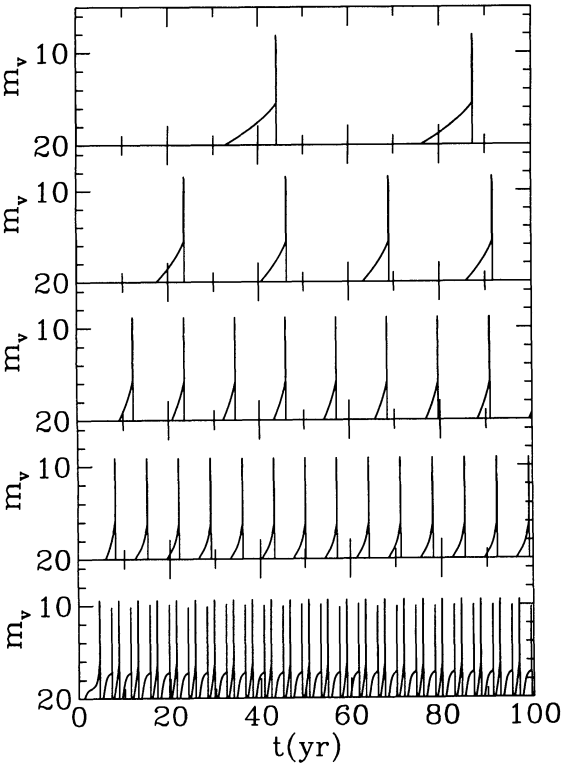

FIG. 3.—The effect of varying $\alpha_{\rm cold}$. For the five panels shown, $\alpha_{\rm hot} = 0.2$, $\dot{M}_T = 2 \times 10^{15}$ g s^{-1}, and $\alpha_{\rm cold} = 0.001$, 0.002, 0.004, 0.006, and 0.10 from top to bottom, respectively.

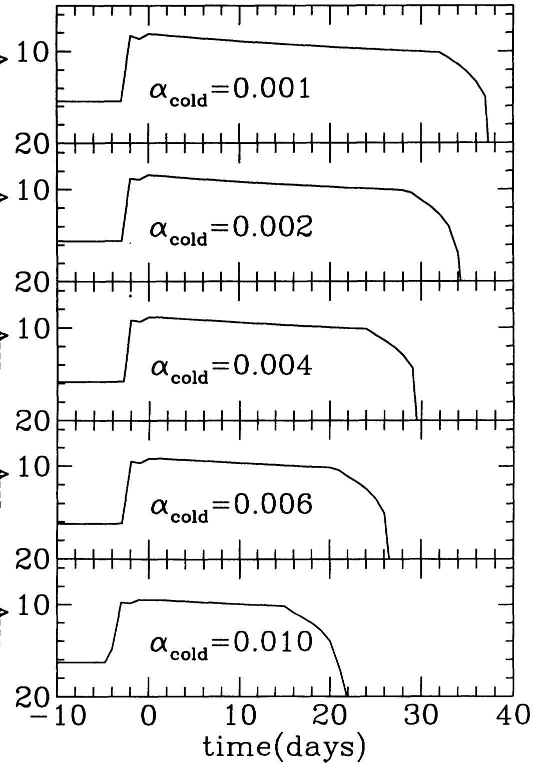

FIG. 4.—An expanded view of single outbursts taken from each panel in Fig. 3.

Figures 2–4 show some effects that may be discernible observationally. The slow rise at about 3–5 mag which occurs for a period of years prior to outburst may account for some of the minimum light variations already seen in some TOADs. The length of the viscous plateau is certainly known to differ among DNs. Long-term minimum magnitude monitoring, plus detailed outburst studies, may provide credence to our models and help determine the values of $\dot{M}_T$ and $\alpha_{\rm cold}$.

The classification scheme devised by Vogt (1993) and Osaki (1993) for systems below the period gap assumes a strict ordering by orbital period for DNs exhibiting a systematic variation in outburst characteristics. We have noted previously that their ordering is not followed by all systems, so the controlling parameter would appear to be something besides orbital period. Furthermore, Osaki has implied an evolutionary picture for his model in that, as the systems below the period gap evolve toward the minimum orbital period (see Paczyński & Sienkiewicz 1981), their rates of mass transfer become smaller (A → B → C). This conjecture is not supported, however, by realistic evolutionary calculations (compare Fig. 4 of Osaki 1994 with Fig. 8 of Kolb 1993) which show $\dot{M}_T$ to be relatively constant below the period gap and above the minimum period. Both Smak (1993) and Osaki (1994) argue that, to obtain the long recurrence times for a system like WZ Sge, one must postulate a much lower value for $\alpha_{\rm cold}$ than has been traditional in the context of DN modeling. One can also increase the recurrence times by decreasing the secondary mass transfer rate $\dot{M}_T$, but even with a very low rate (i.e., $\sim 3 \times 10^{-11}$ $M_\odot$ yr^{-1}), "normal" $\alpha_{\rm cold}$ values of approximately 0.03 would lead (from an extrapolation of the results of

Fig. 3) to outburst recurrence times of about 1 yr. Although our finding that $\alpha_{\rm cold}$ must be small merely confirms their work, it would appear to have more fundamental consequences in terms of the overall schema of the Vogt/Osaki classification, in particular, the sequencing of normal versus superoutbursts. In the model by Osaki (1989a, b) for superoutbursts, a series of normal outbursts (i.e., ones without the viscous plateau) occurs, with a concomitant buildup in disk mass and disk radius as the series progresses. At some point, the outer disk has expanded to the radius $r_{\rm crit}$, at which material orbits in a 3:1 resonance with the binary period. This leads to the formation of an eccentric outer disk and the production of superhumps (Whitehurst 1988). In Osaki's model, the normalization constant appearing in the expression for the tidal torque is increased by default by a factor of 20 when the critical radius is crossed (Ichikawa, Hirose, & Osaki 1993). The increased tidal torque forces a rapid contraction of the outer edge of the disk, which sweeps up material and enhances the surface density by a large factor. The amount of matter now overfills the disk at its new radius relative to $\Sigma_{\rm min}(r_{\rm outer})$, so one must wait for a significant amount of accretion onto the WD to occur before the surface density at the outer edge can decrease to the point at which the cooling front can begin. Thus, this rapid decrease in $r_{\rm outer}$ produces a long, "viscous plateau" type outburst—the superoutburst. In the model of Ichikawa et al. (1993), the tidal torque is increased when $r_{\rm outer} > r_{\rm crit} = 0.46a$ (with a being the orbital separation), and it is not reduced to its normal value until $r_{\rm outer} < 0.38a$.

Now we may appreciate the potential dual role for a decreased $\alpha_{\rm cold}$ in the TOAD systems. Again, we note that an increased recurrence timescale for outbursts accompanies the reduction in the number of normal outbursts that lie between two superoutbursts in Vogt/Osaki's classification. C93b considered the sequencing of long and short outbursts in the DNs. He studied the effect of varying each control parameter in the theory separately and found that several factors can affect the sequencing. In particular, decreasing $\alpha_{\rm cold}$ lengthens the recurrence time, decreases the number of short (or "normal") outbursts lying between two viscous plateau outbursts, and increases the amplitude of the outbursts relative to the quiescent state. These are all factors that are required for the TOADs. In Osaki's superoutburst model, the superoutburst which follows a sequence of normal outbursts is triggered by the final normal outburst, because the expansion of the outer disk edge accompanying that outburst pushes the outer disk edge beyond $r_{\rm crit}$. The ensuing reduction in $r_{\rm outer}$ results in a disk which is overfilled at the outer edge, relative to $\Sigma_{\rm min}$, so that a viscous plateau outburst ensues. We have seen, however, that this is not required. The ratio $\alpha_{\rm hot}/\alpha_{\rm cold} \cong 100$ needed to reproduce the long recurrence times for TOADs also leads to an overfilled disk, in the sense that the resulting outburst must be of the viscous plateau variety. One of the arguments for Osaki's model has been that the recurrence times for the series of normal outbursts leading up to a superoutburst form a monotonically increasing series. This is what Osaki's model predicts, given that $r_{\rm outer}$ increases secularly between superoutbursts and the outbursts are triggered near the outer disk edge. Smak (1991) notes, however, that the observed sequence of recurrence times does not always increase monotonically for VW Hyi (see also Bateson 1977; Smak 1985), the best studied SU UMa system. For about one-third of the series, the recurrence times for the last few outbursts just preceding the next superoutburst become constant or actually decrease. This means the outer disk cannot be continually expanding if the outbursts are starting near the outer edge, and it calls into question the fundamental basis for Osaki's coupled thermal/tidal instability model, i.e., the sudden triggering of increased tidal torque by virtue of $r_{\rm outer} > r_{\rm crit}$. The existence of a precessing, elliptical outer disk giving rise to superhumps is a separate issue. The precessing disk model by Whitehurst (1988) seems to be well supported by observational evidence (e.g., Hessman et al. 1993). It is not clear, however, what effect the presence of noncircularity at large radii will have on the strength of the tidal dissipation produced by the secondary. In particular, we question the motivation for the ad hoc, factor of 20 increase in the tidal torque (Ichikawa et al. 1993) which occurs when $r_{\rm outer} > r_{\rm crit}$.

In summary, Cannizzo (1993b, 1995) has shown that the limit cycle model may possess enough complexity acting alone to lead to changes in the sequencing of long and short outbursts which can explain the observations. We may understand the transition in disk parameters in going from a system like SS Cyg above the period gap, which has from about 1 to 3 short outbursts between two consecutive long outbursts, to one like VW Hyi below the gap, which has between about five and 10 short outbursts between two consecutive long outbursts, by basically adopting the same values for the alphas, but decreasing the disk radius by about a factor of 2 and the mass transfer rate by about a factor of 10 (see Fig. 9 of C93b). We may understand the transition in disk parameters in going from a system in Osaki's class A, such as VW Hyi, to one in his class C, such as WZ Sge, if we keep the mass transfer rate about the same but decrease $\alpha_{\rm cold}$. If we try to lengthen the recurrence times solely by decreasing the mass transfer rate, the response of the disk would be to have more short outbursts sandwiched between two consecutive long ones (see Fig. 9 of C93b and associated discussion), in contrast to what is observed in going from Vogt's class A to C.

What motivation might one have for making $\alpha_{\rm cold}$ so very small for the TOAD systems? If the ordering of Osaki's three classes by mass transfer rate were correct, one could attempt to argue for a physical effect in which lowering $\dot{M}_T$ decreases the level of viscous dissipation in quiescence. Although Osaki's original motivation seems questionable, both because there are systems with orbital periods that do not fit the classes they should and because the expected evolution of mass transfer rate with orbital period due to gravitational radiation is less than Osaki thought, it may still be true that mass transfer variations are the ultimate driving factor. There may be significant variations in $\dot{M}_T$ about the long-term averages which CVs must possess in order to preserve, for example, the observed 2–3 hr period gap (Hameury, King, & Lasota 1989). Observational support for the possibility that $\alpha_{\rm cold}$ might scale with $\dot{M}_T$ is provided by the VY Scl class of DNs which lie just above the period gap. These are systems which are thought to be novalikes most of the time: in a state of high mass transfer in which the disk is always too hot to undergo DN outbursts. Occasionally, however, there are extended periods of time during which the mass transfer rate shuts off, and the system becomes much fainter. It is unavoidable that an interacting binary will dim when the mass transfer rate becomes small because of the decrease in the accretion luminosity. Honeycutt, Cannizzo, & Robertson (1994) have shown, however, that this is in fact not the *immediate* response of the system if the limit cycle disk instability is operating. When the mass transfer rate is turned off in the models, there is a strong tendency for DN outbursts to continue for a long time afterward. This happens because, during a normal, short outburst, only a few percent of the stored matter accretes onto the WD. Many outbursts must occur before the disk mass is depleted by a significant amount. These outbursts are triggered by the viscous evolution of matter in the disk at small radii. The theoretical prediction in the most naive formulation of the model is that, if the mass transfer were suddenly to drop to a low value, one would get a series of ~ 10 DN outbursts of decreasing amplitude and eventually fade to an off state. This is definitely not observed. The obvious way to get around this obstacle is to decrease $\alpha_{\rm cold}$ along with $\dot{M}_T$. This has the effect of elevating $\Sigma_{\rm max}$ immediately and preventing further outbursts.

The physical mechanism by which $\alpha_{\rm cold}$ might respond to changes in $\dot{M}_T$ has not yet been addressed. We require $\alpha_{\rm cold}$ to decrease drastically with $\dot{M}_T$. In the currently favored model by Balbus & Hawley (1991), the viscous dissipation within the disk is provided by the shearing amplification of a weak magnetic field. It may be that at very low disk temperatures, the disk becomes very thin, and the efficiency of this mechanism weakens. C93b found that one of the ways to account for the long-term behavior in the light curve of SS Cyg, in particular, the fluctuations in the recurrence times for outbursts, is to have long-term fluctuations in $\alpha_{\rm cold}$. In the SU UMa systems, if $\dot{M}_T$ were to become very small, the disk temperatures in quiescence could also become small. The computation of the vertical structure of the disk at such low temperatures is uncertain (Cannizzo & Wheeler 1984).

Another possibility is that the TOAD systems have anomalously low mass secondary stars in which $\alpha_{\rm cold}$ is somehow mediated by M_2, perhaps by the tidal torque acting on the outer disk. There may also be problems with this idea. For example, for a low-mass secondary to be still filling its Roche lobe so as to allow mass transfer to proceed, it would have to be even more out of thermal equilibrium than is normal for a system at a given period with a more nearly main-sequence $R_*(M_*)$ relation. For this to be true, the mass-loss time would need to be shorter, i.e., the mass transfer greater. If anything, the TOAD systems appear to have comparable or lower $\dot{M}_T$ values than SU UMa's as a whole. On the other hand, it may be possible to change the secondary radius directly through a variable quadrupole moment produced by magnetic activity in the outer convection zone (Applegate & Patterson 1987).

Finally, there may be some anomalous factor other than $\dot{M}_T$ or M_2 which mediates the viscous dissipation during quiescence and leads to lowered $\alpha_{\rm cold}$ for these systems, perhaps the disappearance of a seed magnetic field in the transferred material from the secondary star. The Balbus & Hawley (1991) mechanism does require a weak magnetic field to begin with, and the magnetic wind from the secondary star which provides the angular momentum loss for systems above the period gap is also thought to become much weaker below the gap, so that the primary angular momentum loss is due to gravitational radiation. There may be periods during which the already low magnetic flux entrained in the mass stream drops completely to zero, or at least below some minimum value, possibly required by the Balbus & Hawley (1991) mechanism. After the field entrained in the disk had been advected onto the WD by the accreting material, there would be no new source of magnetic field. Another possibility is that, during quiescence, the disk may become very thin. The vertical structure would then not be able to resolve as many unstable perturbation wavelengths, so the total number of potentially amplifiable modes would decrease. This might lower $\alpha_{\rm cold}$ from its nominal value of a few hundredths down to a few thousandths until some other viscous dissipation mechanism became active. Although the Balbus & Hawley (1991) mechanism may provide the dominant viscous dissipation and angular momentum transport for disk material if there are magnetic fields in the disk, a host of other mechanisms might come into play at the level $\alpha_{\rm cold} \sim 0.001$ (e.g., weak spiral shocks, convection induced viscous dissipation, internal waves, the baroclinic instability, etc.). Clearly, further work is required both from observations and theory in order to make progress on understanding the cause for TOADs.

4. CONCLUSIONS

We now summarize the list of the properties of the tremendous outburst amplitude DNs.

1. *TOADs.*—To be a TOAD, the outburst amplitude from normal minimum to maximum light must be at least 6 mag. These outbursts are likely to be infrequent and mostly to be superoutbursts. Due to the unknown correction needed for low $\dot{M}_T$ systems (see § 3), we have not attempted any correction to the observed outburst amplitudes.
2. *Orbital Period.*—The TOADs with known orbital periods are *all* below the CV period gap, i.e., less than ~ 2.1 hr (WW Cet and AR And are possible exceptions to this; see comments in § 2).
3. *Mass Transfer Rate and Viscosity* ($\dot{M}_T$ *and* $\alpha_{\rm cold}$).—Our models show that the TOADs at minimum are likely to have very low mass transfer rates, near 10^{15} g s^{-1}. They also have very low values for the viscosity at minimum ($\alpha_{\rm cold} \approx 0.003$). This is needed in order to obtain correct model results. Outburst intervals are long, months to years to decades. There is evidence that TOADs (and indeed other CVs) have variations in their quiescent brightness level. This is interpreted as an indication of variable mass transfer. How large the variation is and what timescale it operates over are unknown at this time. Our modeling shows that to account for the observed properties of these systems (i.e., long recurrence times and only superoutbursts), $\alpha_{\rm cold}$ must be about a factor of 10 smaller than it is for other DNs. It is not sufficient merely to reduce $\dot{M}_T$: that would actually increase the ratio of normal outbursts to superoutbursts.

Systems such as the TOADs described here have been called WZ Sge stars, or WX Cet stars, or possibly just included in the general SU UMa category. But all TOADs are not like WZ Sge or WX Cet or typical SU UMa stars. For example, the WZ Sge stars are believed to be DNs which never have regular outbursts, have longer duration superoutbursts than typical SU UMa stars, and have the shortest orbital periods of the SU UMa's. We see that the TOADs do not fit into any of these categories completely and also appear not to fit in with the general trend of decreasing $\dot{M}_T$ with orbital period (all must be low $\dot{M}_T$). The extremely low viscosity values needed for our models appears to be a unique property.

Future work on the TOADs is needed, in particular distances and M_v's. The latter depend on obtaining good M_v versus inclination models for these systems, as well as understanding how the minimum brightness level varies. Until this is done, their true space positions are highly uncertain. The work of Shara and coworkers, looking for "hibernating" CVs, and our own project of reexamining ESO objective plates looking for faint Hβ emission sources are of particular interest, as both of these projects may find many new candidates to study, increasing the known population of faint CVs. Of the systems with faint apparent magnitudes, we also need to see how many of these systems are indeed intrinsically faint. If the numbers are large (and roughly given by the data in Shara et al. 1993), then the space density of CVs is currently underestimated (by ~ 100). Orbital periods need to be determined for the remainder of the TOADs. This will confirm if they all have short orbital periods. Spectroscopic studies to get radial velocities and system parameters are needed; however, they are extremely difficult, because the TOADs as a class are faint systems. CCD photometry is a viable method for period determination, and about 25%–40% of the systems are likely to show variations in their light output allowing periods to be determined (Howell et al. 1991 and references therein). If we know the period even to a few minutes, that will allow us to determine if they are all ultrashort (i.e., below the period gap). Photometry at superoutburst is also useful, as superhumps are likely to be detectable.

Studies of unconfirmed novae (like GW Lib) may also prove to be highly profitable, as at least some are in fact TOADs, and some are not novae at all. HV Vir (Leibowitz et al. 1994) and V404 Cygni (Wagner et al. 1994) are two recent examples. A long-term study of the minimum light behavior of TOADs is likely to be of importance to our understanding of their mass transfer. For the TOADs, we are likely to derive information on episodic events and/or be able to watch the accretion disk grow from nothing to its preoutburst state (as predicted by our models in § 3). A study of this type is underway for novalike stars by Jurcevic et al. (1994) and has shown interesting results on their long-term behavior. And finally, theoretical studies of these and related systems, such as those begun by Osaki (1993, 1994), Sparks et al. (1993) and Livio (1993), and in this work, are needed to determine the cause of the large outburst amplitudes and the evolutionary paths for the TOADs.

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