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SXTs AND TOADs: CLOSE ENCOUNTERS OF THE SAME KIND

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ABSTRACT

We show that, apart from having in common long intervals between large-amplitude outbursts (without intervening normal outbursts), soft X-ray transients (SXTs) and "tremendous outburst amplitude dwarf novae" (TOADs) have very similar optical light curves, showing glitches and superhumps during the main part of the outbursts, and considerable postoutburst activity in the form of one or more minioutbursts. We propose that these similarities reflect that both SXTs and TOADs have very small mass ratios and very low mass transfer rates. The outbursts of SXTs and TOADs are triggered by a viscous instability and are almost always followed by a tidal instability during which superhumps develop. We suggest that the increased mass accretion during the glitches is caused by enhanced tidal dissipation.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual (GRO J0422+32, AL Comae Berenices, UZ Bootis) — X-rays: stars

1. INTRODUCTION

Soft X-ray transients (SXTs), or X-ray novae, are a subclass of the low-mass X-ray binaries (LMXBs), distinguished by the presence of outbursts of X-rays alternating with intervals of quiescence lasting on the order of a year or longer (see White, Kaluzienski, & Swank 1984), during which the X-ray flux is extremely low (see, e.g., Verbunt et al. 1994). For several of the SXTs, there is dynamical evidence that the compact object is a black hole (see van Paradijs & McClintock 1995; Tanaka & Lewin 1995 for recent reviews). Together with the X-ray outbursts, the optical emission increases, due mainly to X-ray heating of the accretion disk, with optical outburst amplitudes ranging between ~2 and ~7 mag. A useful compendium of the X-ray and optical outbursts of SXTs has been published by Chen, Shrader, & Livio (1996).

Recently, Howell, Szkody, & Cannizzo (1995a) distinguished a particular type of dwarf novae, characterized by the very large amplitudes of their optical outbursts (6–10 mag) and the very long intervals between these outbursts (months to decades). They called them "tremendous outburst amplitude dwarf novae," or "TOADs." These TOADs are a subset of the SU UMa systems, i.e., dwarf novae that show both "normal outbursts" and "superoutbursts." During the superoutbursts (lasting 2–3 weeks), periodic brightness variations are seen ("superhumps"), with periods that are several percent longer than the orbital period. Apart from the very long intervals and the very large amplitudes, TOADs also differ from the other SU UMa systems in that almost all TOAD outbursts are superoutbursts (see Howell et al. 1995a for details). For a comprehensive review of dwarf novae we refer to the recent book by Warner (1995b).

The possibility that the outbursts of SXTs and dwarf novae might be caused by the same mechanism has already been recognized by, e.g., van Paradijs & Verbunt (1984) and Priedhorsky & Holt (1987). The origin of the outbursts is still the subject of debate; they are probably caused by a thermal instability in the disk or a mass transfer instability in the companion star (see Lasota 1996 and references therein). Recently, van Paradijs (1996) presented evidence that the outbursts of SXTs and dwarf novae are both caused by accretion disk instability and showed that X-ray heating has a stabilizing effect on the disk.

We argue here that, in comparing the unstable members of LMXBs and cataclysmic variables (CVs), we should not juxtapose SXTs with dwarf novae, in general, but limit the latter to the TOADs. We will outline the similarities between SXTs and TOADs, and their differences, and briefly discuss possible explanations for their behavior.

2. COMPARISON BETWEEN SXTs AND TOADs

2.1. *Optical Outburst Light Curves*

In this subsection we describe the optical light curves of SXTs and TOADs. We will consider the three best-studied cases, one SXT and two TOADs.

Optical outburst light curves of SXTs are fragmentary and generally cover only the main outburst (see van Paradijs & McClintock 1995; Tanaka & Lewin 1995 and references therein). This is primarily due to the long time base needed to monitor these outbursts. The only SXT that has been extensively covered to date is GRO J0422+32 (Nova Per 1992). The optical light curve of this system is reproduced in Figure 1*a*. The system brightened by ~7.5 mag up to $V \sim 13$ mag and subsequently decayed slowly (0.0085 mag days^{-1}) in the next ~200 days. A "glitch," with an X-ray flux increase of a factor ~2.5 about 120 days after the onset of the outburst, is only slightly visible in the optical light curve ($\Delta V \sim 0.3$ mag;

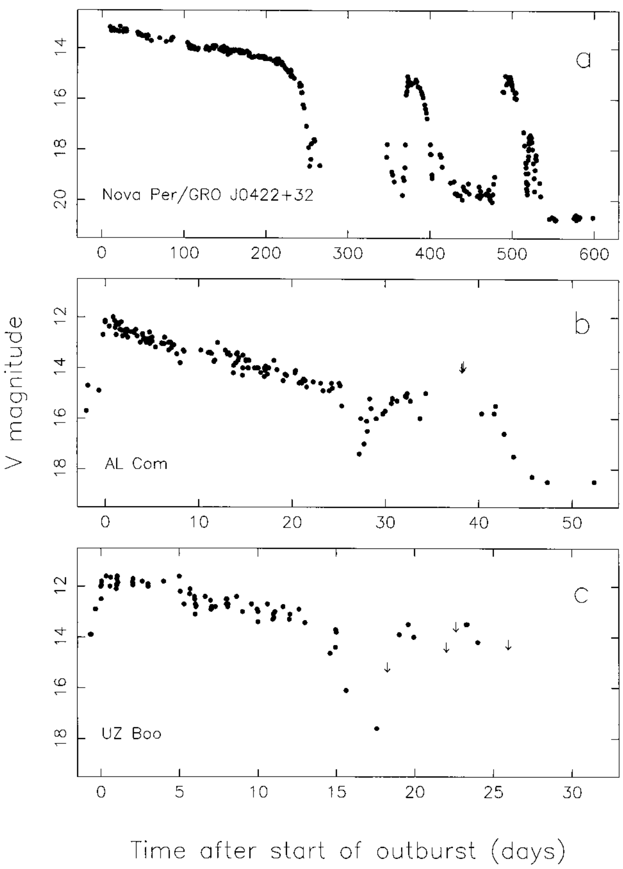

FIG. 1.—Outburst light curves of one SXT and two TOADs. (*a*) The SXT GRO J0422+32 (Nova Per 1992); data from Mineshige (1994), Callanan et al. (1995), Chevalier & Ilovaisky (1995), Kato et al. (1995), and measurements reported in IAU Circulars, see Chevalier & Ilovaisky (1995). The TOADs (*b*) AL Com and (*c*) UZ Boo. The arrows in panels (*b*) and (*c*) denote "fainter than" observations. Both the SXT and TOADs show, after the general decay of the main outburst, a temporary minimum followed by reversal(s) to a high flux level (see text for details).

Callanan et al. 1995; Chevalier & Ilovaisky 1995). The brightness suddenly dropped by 4 mag after the long decay, within ~20 days. About ~370 and ~480 days after the start of the main outburst, two "minioutbursts" were observed; both reached a maximum of $V \sim 14.5$ mag ($\Delta V \sim 5$ mag) and lasted for ~20–30 days (with a decay rate of ~0.2 mag day^{-1}). The maximum of the first minioutburst falls just above the extrapolated exponential decay of the main outburst. Moreover, even smaller amplitude (~2 mag) outbursts can be seen in the light curves that occur after the main outbursts and after both minioutbursts. Also, in Nova Vel 1993 minioutbursts ($\Delta V \sim 2$–4 mag) were seen after the main outburst (Bailyn & Orosz 1995).

Quiescence observations showed that GRO J0422+32 has an orbital period of ~5.1 hr (Chevalier & Ilovaisky 1996 and references therein) and a mass ratio q ($\equiv M_2/M_1$)[1] ~ 0.1. Based on dynamical mass measurements, it is suspected that this SXT contains a black hole (Filippenko, Matheson, & Ho 1995b).

Only a few TOADs have been well studied during their superoutbursts. Two of them, AL Com and UZ Boo, have been observed both during their main outburst and for some time afterward. This makes them suitable for a detailed comparison with the SXT optical outburst light curves.

The observations of AL Com show that outbursts occur irregularly at intervals on the order of 10 yr. AL Com has an orbital period of ~1.3 hr (Howell et al. 1995a, 1996; Kato et al. 1996). In Figure 1*b* we show the 1995 superoutburst light curve (Howell et al. 1996). After an increase of ~8 mag, the brightness decayed at a rate of ~0.12 mag day^{-1} for ~25 days. The light curve shows a small glitch ($\Delta V \lesssim 1$ mag) ~ 10 days after the start of the outburst (this phenomenon has been interpreted as a standstill by Howell et al. 1996). After the main outburst, the light curve shows a brief minimum ($\Delta V \sim 2.5$ mag) for a few days, after which AL Com rose again, to continue just above the extrapolated exponential decay of the main outburst. About 40 days after the outburst, the system is still bright ($V \sim 16$ mag) and then decays within a few days to quiescence. Unfortunately, no firm measurements (only a limit of $V \gtrsim 14$ mag at day 38) are available between day ~34 and ~40 to indicate whether there are two minioutbursts or just one that lasted for ~10 days.

The 1994 superoutburst light curve of UZ Boo (Hurst 1994; see Fig. 1*c*) shows a structure similar to AL Com. It decayed at a rate of ~0.09 mag day^{-1}, and a small glitch in the light curve occurred ~5 days after the start. In this system the brief minimum ($\Delta V \sim 4$ mag) is more clearly visible than in AL Com; it occurred ~14 days after outburst start, lasted for several days, and was followed by two smaller outbursts. The orbital period of UZ Boo is between ~1.4 and 2.2 hr, as is inferred from superhump observations (G. M. Hurst 1995, private communication).

Brief minima have also been observed during superoutbursts of other TOADs, such as WZ Sge and VY Aqr (Patterson, Williams, & Hiltner 1981; Richter 1992; Howell et al. 1995b, 1996).

Comparing the SXT GRO J0422+32 with the TOADs AL Com and UZ Boo, we see that their outburst light curves show similar characteristics. During the slow decay phase of the outburst, a glitch in the light curve (of similar magnitude, i.e., 1 mag, in AL Com and UZ Boo [optical] and GRO J0422+32 [X-rays; see Callanan et al. 1995; Chevalier & Ilovaisky 1995]) appears. After the glitch, the outbursts decay further at the same rate as before and finally show a sharp drop in brightness. Such a sharp drop after a long, slow decay phase was also observed in the SXT A0620−00 (Tsunemi, Matsuoka, & Takagishi 1977; Lloyd, Noble, & Penston 1977). After the main outburst, GRO J0422+32 showed two additional small outbursts separated by deep minima, each lasting for about 1 month. Although the coverage of the light curves after the temporary minima is insufficient to specify their functional dependence in detail, the light curves of UZ Boo and AL Com similarly showed one or two additional brightenings after the brief temporary minima.

SXTs and TOADs in general both have long recurrence times and large-amplitude outbursts, with similar rise times. The decay times of SXTs and dwarf novae differ by roughly a factor of 10 (see also Cannizzo 1994). We note that not all the SXTs have simple light curves, such as GRO J0422+32 and A0620−00, i.e., a single rise and a slow decay (see, e.g., White et al. 1984). Recent examples are GRS 1915+105 (e.g., Harmon, Paciesas, & Fishman 1994) and GRO J1655−40 (Bailyn et al. 1995; Harmon et al. 1995), which showed a lot of activity in X-rays after their main outburst.

[1] M_1 and M_2 are the masses of the primary and secondary, respectively.

2.2. *Timescales and Superhumps*

The duration of the main outburst of GRO J0422+32, the time of occurrence of the glitch, and the interval between the peaks of the minioutbursts are all multiples of ∼120 days, as was already noted by Callanan et al. (1995) and Chevalier & Ilovaisky (1995), and predicted by Augusteijn, Kuulkers, & Shaham (1993). Glitches similar to GRO J0422+32 have been seen in several other SXTs (see Chen, Livio, & Gehrels 1993, and references therein). In the two TOADs, it appears that the interval between the start of the outburst and the glitch and the interval between the minioutbursts are also comparable, i.e., ∼5 days in UZ Boo and probably ∼10 days in AL Com. This is a factor of 10–25 shorter than in GRO J0422+32.

Superhumps have been reported during the outbursts of several SXTs (Charles et al. 1991; Bailyn 1992; Kato, Mineshige, & Hirata 1995). Kato et al. (1995) reported that the superhumps in GRO J0422+32 did not appear until ∼100 days after the start of the outburst, just before the first glitch occurred. These superhumps disappeared, however, at the time of the X-ray glitch and did not reappear thereafter. Instead, variations at the orbital period were then seen (Callanan et al. 1995; Chevalier & Ilovaisky 1995; Kato et al. 1995). In TOADs, superhumps also appear late in the outburst (latest in the shortest period systems; Vogt 1993). The delay of their onset since the start of the outburst was 10–13 days in WZ Sge (Patterson et al. 1981), 8–10 days in AL Com (Kato et al. 1996; Howell et al. 1996), and 4–7 days in UZ Boo (G. M. Hurst 1995, private communication); we note that these superhumps appear near the first glitch in AL Com and UZ Boo. In typical SU UMa stars, such as VW Hyi or Z Cha, superhumps appear earlier, 1–3 days after the onset of the outburst (see Warner 1995a, b).

3. DISCUSSION

Van Paradijs (1985) and Warner (1987) already suggested that large-amplitude outburst dwarf novae are associated with systems that have low-mass transfer rates during minimum. TOADs have the lowest known mass accretion rates ($\dot{M} \sim 10^{15}$ g s^{-1}) of the CVs; they probably form a continuum with the SU UMa systems as far as $\dot{M}$ goes (Howell et al. 1995a). The SXTs have the lowest time-averaged $\dot{M}$ of the LMXBs (see Tanaka & Lewin 1995). Their mass accretion rates are lower than those of typical dwarf novae with similar orbital periods, because at such higher $\dot{M}$ values they would be stable against outbursts because of X-ray heating (van Paradijs 1996).

Superhumps are known to appear only in systems that have a mass ratio $q \lesssim 0.22$ (Molnar & Kobulnicky 1992). Indeed, SXTs (e.g., Orosz et al. 1994; Filippenko et al. 1995b; Filippenko, Matheson, & Barth 1995a; and references therein) and TOADs (see Warner 1995a) both have very low q values, typically between 0.05 and 0.15. In these systems it is thought that a tidal instability (Whitehurst 1988) is triggered after the disk expands to its tidal resonance radius during a thermal disk instability outburst (Osaki 1989; Ichikawa, Hirose, & Osaki 1993; Ichikawa, Mineshige, & Kato 1994), and superhumps are generated because of enhanced tidal dissipation at the 3:1 resonance point (see Ichikawa et al. 1993; Whitehurst 1994; and references therein). We note that the observed period excesses of the superhump, 1%–2% larger than the orbital period in SXTs (Nova Mus 1991, Remillard, McClintock, & Bailyn 1992; GRO J0422+32, Kato et al. 1995) and TOADs (WZ Sge, Patterson et al. 1981; HV Vir, Leibowitz et al. 1994; AL Com, Kato et al. 1996 and Howell et al. 1996), also point to very low q values (Molnar & Kobulnicky 1992; Whitehurst 1994).

It was already suggested by Kato et al. (1995) that the tidal instability is the origin of the superhumps *and* the glitch in GRO J0422+32. We suggest that the tidal instability produces the same features in the TOAD outburst light curves. The SXT and TOAD outbursts (and the superoutbursts of the SU UMa stars) have two stages: (1) a viscous instability during which the disk radius increases; and (2) when the disk radius exceeds the tidal resonance radius, the superoutburst stage with superhumps. The tidal dissipation enhances the mass accretion, which shows up as a brief enhancement in the brightness, i.e., the glitch. The occurrence of glitches in black hole transients has recently been the subject of several papers (Chen et al. 1993; Augusteijn et al. 1993; Mineshige 1994; Ichikawa et al. 1994). If the glitches in the optical light curves of TOADs have the same origin as those in black hole transients, they may also show up in the UV or soft X rays.

The accretion disks in SXTs are substantially larger than those in TOADs because of the larger orbital periods and compact star masses in the former. The same is the case for the disk mass available when superoutbursts occur (see Osaki 1989; Warner 1995a). The difference in SXT and TOAD disk radius and mass is about a factor of 10–20. It is this difference that is the likely origin of the longer timescales of the outbursts of SXTs compared to those of the TOADs, both with regard to their total duration and to the delay between the onset of superhumps and glitches in SXTs (the former arise in the outer disk, the latter near the compact star).

The observed rapid decline in the optical, as well as in X-rays, at the end of the main (super)outburst occurs probably because of a cooling wave that starts in the outer disk and propagates inward through the disk (e.g., Cannizzo 1993; Ichikawa et al. 1994). These cooling waves can only start when enough material is depleted. If there is still some material piled up just behind this cooling wave, it might be reflected as a heating wave and may produce a second or even a third outburst (see Howell et al. 1996 for theoretical and observational evidence). In typical SU UMa stars, which show many normal outbursts between superoutbursts, the disk will become depleted of most of its stored material (Ichikawa et al. 1993). However, in the TOADs and SXTs normally no normal outbursts occur, so that the outer disk may still contain enough matter to reflect the cooling wave as an inward moving heating front and can start another outburst. In fact, the light curves shown in this paper indicate that one or two such minioutbursts occur.

The very low mass transfer rates and infrequent outbursts seen in the SXTs and TOADs force current disk models to use extreme values for some physical parameters (Osaki 1989; Howell et al. 1995a; Lasota 1996), in particular, a very small value for the quiescent viscosity, i.e., $\alpha_{\text{cold}} \lesssim 0.001$, compared to $\alpha_{\text{cold}} \sim 0.01$ for typical SU UMa stars (see Lasota 1996). This low value is needed to allow the disk to store material for long times before an outburst occurs. We note that Cannizzo, Chen, & Livio (1995) present an alternative model in which there is a dependence of α on the local aspect ratio. When the disk conditions are such that an outburst does occur, the value of the viscosity during outburst, α_{hot}, is essentially the same as in typical dwarf novae, but the larger amount of stored material causes a tremendous amplitude outburst in which the disk expansion is also large enough that essentially every outburst reaches the tidal radius and is a superoutburst (see Howell et al. 1996 in the case of AL Com). The tidal resonance radius in the SXT disks is larger then in TOADs, so the expansion of the disk to that radius takes longer, as is reflected in the outburst light curves. X-ray heating present during the main outburst in SXTs (see Callanan et al. 1995; van Paradijs 1996) may also help in prolonging the outburst (e.g., Chen et al. 1993).

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