Outbursts of WZ Sge stars/TOADs: a phenomenological comparison with soft X-ray transients

Erik KUULKERS
Space Research Organization Netherlands, Sorbonnelaan 2, 3584 CA Utrecht, & Astronomical Institute, Utrecht University, P.O. Box 80000, 3507 TA Utrecht, The Netherlands, E.Kuulkers@sron.nl

Abstract

The outbursts of WZ Sge stars (or TOADs), are compared to those seen in the (soft) X-ray transients. Both types of outbursts exhibit strong similarities: large amplitudes, long recurrence times, occurrence of superhumps, and of rebrightenings or reflares at the end or just after the main outburst. This suggests that the same kind of mechanism is at work to produce these outbursts. I also briefly discuss their differences and whether superoutbursts may exist among the very long (> month) outbursts in U Gem stars.

1. Introduction

The recognition that outbursts seen in soft X-ray transients (SXTs, where the compact star is a neutron star or black hole) show similarities to those seen in the unstable class of cataclysmic variables (CVs, where the compact star is a white dwarf) started with the discovery of the brightest X-ray transient so far, i.e., A0620−00 (Elvis et al. 1975). The detection at other wavelengths followed soon thereafter (for a review see Kuulkers 1998). Analysis of archival plates showed another outburst which occurred ~60 years earlier, in 1917 (Eachus et al. 1976). The large optical outburst amplitude (~8 mag) and long recurrence time were found to be comparable to those of recurrent novae, including the dwarf novae (DNe) WZ Sge, AL Com and VY Aqr (e.g., Eachus et al. 1976; Kholopov & Efremov 1976). Based on the luminosity of A0620−00 in X-rays it was suggested that the compact star in this system was a neutron star or black hole (e.g., Elvis 1998).
et al. 1975). Ten years later it was dynamically established to be a black hole (McClintock & Remillard 1986).

Mainly the availability of all-sky X-ray monitors increased the sample of X-ray transients with well covered outburst light curves (e.g., White et al. 1984; for a recent compendium of SXTs light curves I refer to Chen et al. 1997). It was noticed by van Paradijs & Verbunt (1984), through a comparison of a sample of SXTs and DNe, that they had comparable rise times to maximum, and that, therefore, the nature of their outbursts may be similar. The optical outburst amplitudes of SXTs range from 2 to 9 mag (e.g., Shahbaz & Kuulkers 1998), a range also seen in DNe (e.g., Warner 1995). To date, various other characteristics of dwarf novae outbursts are also found in SXTs, strengthening their similarity. A nice example is the delay between the start of the outburst in the UV and optical in DNe (e.g., Polidan & Holberg 1987), which has been observed in the form of an X-ray delay with respect to the optical in SXTs (e.g., Orosz et al. 1997).

2. A phenomenological comparison

2.1. SU Uma stars

A subgroup of the DNe, the SU UMa stars, shows both short (\sim\text{days}) and long (\sim\text{weeks}) outbursts. The long outbursts, called superoutbursts, are much less frequent than the short outbursts (normal outbursts), and are somewhat brighter (\sim\text{1 mag}). During superoutbursts a unique feature develops: a photometric variation with a period, $P_{\text{sh}}$, a few % longer than the orbital period, i.e., the superhump. In Fig. 1, I show the observed superhump period excess, $\epsilon$, vs. the orbital period, $P_{\text{orb}}$, for SU UMa stars (see Patterson 1998 and in these proceedings).\footnote{This sample includes systems which are permanently in a high accretion state, so-called “permanent superhumpers”}.

The recurrence times of normal outbursts are rather erratic. For superoutbursts they are more stable; however, they may change from time to time (Vogt 1980). More or less stable recurrence times have also been found in various SXTs (see Priedhorsky 1986). For example, one of them, 4U 1630−47, showed outbursts every \sim600 days. Recently, it was found that its outburst recurrence time had changed to \sim680 days, very similar to what is seen in SU UMa stars (Kuulkers et al. 1997).

At one of the extreme ends of the SU UMa stars are the stars with long outburst recurrence times; for them almost every outburst is a superoutburst. Such stars are known as WZ Sge stars (e.g., Bailey 1979), sometimes referred to as TOADs (Howell et al. 1995). It is this subgroup which indeed shows the
Table 1. Some properties of various SXTs

| SXT                             | P$_{\text{orb}}$ (hr) | $\epsilon=(P_{\text{sh}}-P_{\text{orb}})/P_{\text{orb}}$ | $q=M_2/M_1$ (M$_\odot$) | M$_1$ |
|---------------------------------|------------------------|----------------------------------------------------------|-------------------------|-------|
| GRO J0422+32 (Nova Per '93)    | 5.09                   | 0.0167±0.0056                                            | <0.083                  | 10±5  |
| A0620−00 (Nova Mon '75)        | 7.75                   | -                                                        | 0.067±0.004             | 10±5  |
| GS 2000+25 (Nova Vul '88)      | 8.26                   | 0.0096±0.0009                                            | 0.042±0.017             | 10±4  |
| GS 1124−68 (Nova Mus '91)      | 10.40                  | 0.0099±0.0028                                            | 0.125±0.031             | 6$^{+5}_{-2}$ |
| Cen X-4 (Nova Cen '69)         | 15.1                   | -                                                        | 0.20±0.04               | 1.3±0.6 |
| GRO J1655−40 (Nova Sco '94)    | 62.9                   | -                                                        | 0.28±0.07               | 7±1   |
| GS 2023+34 (V404 Cyg)          | 155                    | -                                                        | 0.059±0.003             | 12±2  |

a Data taken from O’Donoghue & Charles (1996) and Charles (1998).

The strongest similarities with the SXTs (Kuulkers et al. 1996; see also Lasota 1995). Note that ‘normal’ SU UMa stars may also exhibit long intervals of no outbursts during which the source is fainter than normal, such as HT Cas (e.g., Robertson & Honeycutt 1996). On the other hand, some WZ Sge stars may show periods of more regular outburst behaviour during which the source is somewhat brighter in quiescence than normal, such as BZ UMa (Jurcevic et al. 1994).

2.2. Superhumps in soft X-ray transients

The detection of photometric variations with a period slightly larger than the orbital period during outbursts of SXTs immediately pointed to superhumps (e.g., Charles et al. 1991, Callanan & Charles 1991; see O’Donoghue & Charles 1996). In Table 1 I show the SXTs for which both the orbital period (P$_{\text{orb}}$) and q are known. In three cases the outburst data reveal clear evidence for superhumps with a period only 1–2% longer than the orbital period. These three SXTs can also be found in Fig. 1. The short superhump period excesses are very similar to those found in various WZ Sge stars (e.g., Kuulkers et al. 1996, Patterson et al. 1996).

A correlation between superhump period excess, $\epsilon$, and mass ratio, q, was predicted by Whitehurst (1988) and confirmed by Molnar & Kobulnicky (1992). As shown by Patterson (1998) this relation is roughly $\epsilon = 0.23q/(1+0.27q)$, which allows one to estimate q solely from the superhump period excess. Note that the observed values of q in GRO J0422+32 and GS 2000+25 agree with this relation, but does not for GS 1124−68. At the right side of Fig. 1a I supply an additional scaling for q based on this relation. Theoretically it has been argued that su-
Fig. 1. (a) The observed superhump period excess, $\epsilon$, as a function of the orbital period, $P_{\text{orb}}$, for SU UMa stars and permanent superhumpers. Superhump theory predicts a relation between $\epsilon$ and the mass ratio, $q$, which is indicated at the right (after Patterson 1998). Included are the SXTs in which clear evidence for superhumps is seen (Table 1). The known values of $q$ and $P_{\text{orb}}$ for U Gem are also plotted; see text. (b) The 1994 superoutburst light curve of UZ Boo as compiled from the AAVSO, BAAVSS, VSNET and VSOLJ reports. Errors denote upper limits. This is an update from Kuulkers et al. (1996).

perhumps only appear in systems with mass ratio $q \lesssim 0.33$ (Whitehurst & King 1991, Whitehurst 1994). It is, therefore, not surprising that given their values for $q$ (Table 1), superhumps are seen in SXTs as well (see, e.g., also Whitehurst 1994). As noted by Patterson (1998) the inferred values of $q$ from $\epsilon$ range up to $\sim 0.5$ for SU UMa stars and permanent superhumpers, in contradiction with superhump theory.

2.3. Superhump growth time and secondary maximum

Superhumps in WZ Sge stars and SXTs have long growth times, i.e., they appear one or two weeks, respectively, months, after the outburst has started. In ‘normal’ SU UMa stars they appear after one to several days (e.g., Vogt 1993). This is due to the fact that the strength of the tidal instability decreases below $q \sim 0.1$ (e.g., Molnar & Kobulnicky 1992, Whitehurst 1994).

The start of the superhumps in at least GRO J0422+32 was seen to be very close to the start of the secondary maximum, which suggests a possible connection between the two (Kato et al. 1995). The same can be inferred for some of the WZ Sge stars, e.g., AL Com and EG Cnc (see Patterson et al. 1996, 1998). It was, therefore, suggested that the origin of the superhumps and secondary maximum
are the same for both the SXTs and WZ Sge stars (Kuulkers et al. 1996).

2.4. Rebrightenings/reflares

Reflares after the main outburst or sudden drops with a rebrightening near the end of the outburst are present in several WZ Sge stars (see Richter 1992, Kuulkers et al. 1996; e.g., UZ Boo: Fig. 1b). The best example of reflares is EG Cnc which showed up to six ‘normal’ outbursts after its main outburst (Patterson et al. 1998, Kato et al. 1998). The best example of a rebrightening is WZ Sge itself, which showed a fast drop near the end of the 1978 outburst but came back to stay on for a longer time. It then gradually decayed to quiescence (Ortolani et al. 1980, Patterson et al. 1981). Reflares/rebrightenings are, however, not exclusively seen in WZ Sge stars: SU UMa also showed a reflare after its 1989 outburst (Udalski 1990).

In SXTs reflares have been observed as well. GRO J0422+32 is the best known example (Callanan et al. 1995, Chevalier & Ilovaisky 1995): it showed two strong and various weaker outbursts after its main outburst. The SXT 4U 1543−47 showed multiple rebrightenings/reflares in X-rays during its 1971/1972 outburst (Li et al. 1976). In GRO J0422+32 the two strong reflares appeared ∼120 days after each other, which is similar to the time from maximum to the secondary maximum of the outburst (e.g., Callanan et al. 1995). This also holds for the reflares seen in the WZ Sge stars (see Kuulkers et al. 1996). A good example is again EG Cnc (see Kuulkers & Howell 1996): a clear secondary maximum can be seen about a week after outburst maximum, whereas the reflares appeared a week apart (see, e.g., Patterson et al. 1998). This may indicate a certain clock which operates in both the SXT and WZ Sge stars which controls the timing of the secondary maximum (and/or onset of superhumps) and the time between reflares.

3. Discussion

3.1. Differences

Although I have shown here that there are similarities in the outburst behaviour of SXTs and WZ Sge stars/TOADs, obvious differences are present as well. The main difference is the fact that SXTs harbour a neutron star or a black hole instead of a white dwarf. A black hole (≳3 M_⊙) can easily account for the observed low values of q. The presence of such compact stars leads to more energetic outbursts, especially in the X-ray and γ-ray region. Strong radiation at these wavelengths almost certainly irradiate the disk and/or secondary star and may influence the duration and/or brightness of the outbursts of SXTs (e.g., van
Fig. 2. (a) Visual estimates of the 1995 outburst of U Gem done by the AAVSO, AFOEV, BAAVSS and VSOLJ. Arrows denote upper limits. (b) Averages (15 consecutive points) of the outburst light curve of (a). The errors are the mean absolute deviations per bin (see Press et al. 1992).

Paradijs & Verbunt 1984, van Paradijs & McClintock 1994, Shahbaz & Kuulkers 1998). In DNe, irradiation of the accretion disk is probably not very important (e.g., Hameury et al. 1998). However, the hot white dwarf, heated during outburst, may influence the very cool (e.g., Ciardi et al. 1998) secondary star in WZ Sge stars. This could account for the presence of reflares/rebrightenings in such systems (Warner 1998, see also Lasota in these proceedings). In this respect I note the striking similarity in the outburst amplitude and morphology of the outburst light curves of A0620−00 and AL Com (Kuulkers 1998). The only difference is the timescale of their outburst duration by a factor ∼5. If irradiation influences the outburst brightness in A0620−00 it remains unclear why a similar outburst amplitude can be seen in AL Com; maybe irradiation has less effect on brightness than expected.

3.2. Superoutbursts in U Gem stars?

Very long (>month) outbursts seem to be very rare among DNe above the period gap, where most of them belong to the U Gem class. Lasota (1995) made me aware of a ‘sketch’ in Mason et al. (1988) of a long (∼40 days) outburst of U Gem which occurred in 1985. This was not seen before in this system; the outburst durations are normally bimodally distributed (∼9 and ∼17 days; see, e.g., van Paradijs 1983). Fig. 2a shows a compilation of the available visual estimates during that time. The long outburst is reminiscent to that seen in WZ Sge stars. The individual measurements suggest a secondary maximum after
more than a week, as can be seen in some WZSge star outburst light curves (Sect. 2.4). However, statistically this may not be significant (Fig. 2b). It is interesting to speculate that this long outburst is in fact a superoutburst and thus may have exhibited superhumps. A crazy idea is to put U Gem in Fig. 1a, given $q = 0.46 \pm 0.03$ and $P_{\text{orb}} = 4.25\text{ hr}$ (Friend et al. 1990). Surprisingly, the inferred value of $\epsilon$ of U Gem (~9.5%) is close to the extreme end of the $\epsilon$ vs. $P_{\text{orb}}$ relation. No observations have been done during the 1985 outburst of U Gem to confirm the presence of superhumps. It has been argued earlier that the long outbursts in U Gem stars may in fact be superoutbursts (van Paradijs 1983). However, no superhumps have been seen in the long outbursts (~2 weeks) of e.g., SS Cyg, despite considerable coverage (Honey et al. 1989). Moreover, the recurrence time properties of the long outbursts in U Gem stars are different to that of the superoutbursts in SU UMa stars (see Warner 1995). It is interesting to note (see Warner 1995) that the only SU UMa star so far above the period gap, i.e., TU Men ($P_{\text{orb}} = 2.82\text{ hr}$), has a trimodal distribution of outburst widths, i.e., short (~1 day), long (~8 days) and superoutbursts (~20 days). It could therefore be that U Gem’s outburst duration distribution also follows a trimodal distribution, where superoutbursts are very rare.

Among the WZSge star candidates a few have (inferred) orbital periods above and just below the period gap (see, e.g., O’Donoghue et al. 1991, Howell et al. 1995). These may be candidates of systems which have evolved way past the period minimum (Howell et al. 1997; see, however, Patterson 1998). Among these are EF Peg (Howell et al. 1995); superhumps were seen during its 1991 outburst with $P_{\text{sh}} \simeq 2.05\text{ hr}$ (Howell & Fried 1991, Kato & Takata 1991). The candidates above the period gap were e.g. DO Dra, AR And and WW Cet (Richter 1985, O’Donoghue et al. 1991), Howell et al. 1995). They seemed to have long outburst recurrence times and large amplitude outbursts. However, a closer look of the candidates above the period gap have revealed that they are normal U Gem stars (see Ritter & Kolb 1998, and references therein). Future observations are needed to see whether EF Peg is a real WZSge star, and whether WZSge stars indeed exist above the period gap. Such observations have large implications on our understanding of evolution of CVs among the period minimum (Howell et al. 1997, Patterson 1998). Moreover, such stars, having larger orbital periods, might then be even closer cousins to the SXTs.

**Acknowledgements:** In this paper we have used, and acknowledge with thanks, data from the AAVSO International Database, based on observations submitted to the AAVSO by variable star observers worldwide, as well as observations of the AFOEV, BAAVSS and VSOLJ, and from VSNET. Most of this work is entirely
attributed to “the zeal and assiduity, not only of the public observers, but also of the many private individuals, who nobly sacrifice a great portion of their time and fortune to the laudable pursuit” of these variables (Moyes 1831).

4. References

Bailey J. 1979, MNRAS 189, 41P
Callanan P.J., Charles P.A. 1991, MNRAS 249, 573
Callanan P.J., et al. 1995, ApJ 441, 786
Charles P.A. 1998, in: Theory of Black Hole Accretion Disks, CUP, p. 1
Charles P.A., et al. 1991, MNRAS 249, 567
Chen W., et al. 1997, ApJ 491, 312
Chevalier C., Ilovaisky S.A. 1995, A&A 297, 103
Ciardi D.R., et al. 1998, ApJ 504, 450
Eurchu L.J., et al. 1976, ApJ 203, L17
Elvis M., et al. 1975, Nat 257, 656
Friend M.T., et al. 1990, MNRAS 246, 637
Hameury J.-M., et al. 1998, MNRAS, in press (astro-ph/980347)
Honey W.B., et al. 1989, MNRAS 236, 72
Howell S.B., Fried R. 1991, IAUC 5372
Howell S.B., et al. 1995, ApJ 439, 337
Howell S.B., et al. 1997, MNRAS 287, 929
Jurcevic J.S., et al. 1994, PASP 106, 481
Honey W.B., et al. 1989, MNRAS 236, 727
Kato T., Takata T. 1991, IAUC 5371
Kato T., et al. 1995, PASJ 47, 163
Kato T., et al. 1998, PASJ, in press
Kuulkers E., Efremov Yu.N. 1976, PZ 20, 277
Kuulkers E. 1998, NewAR 42, 1 (astro-ph/9805031)
Kuulkers E., Howell S.B. 1996, VSNET-alert 654
Kuulkers E., et al. 1996, ApJ 462, L87
Kuulkers E., et al. 1997, MNRAS 291, 81
Lasota J.-P. 1995, in: Compact Stars in Binaries, IAUS 165, p. 43
Li F.K., et al. 1976, ApJ 203, 187
Mason K.O., et al. 1998, MNRAS 232, 779
McClintock J.E., Remillard R.A. 1986, ApJ 308, 110
Molnar L.A., Kobulnicky H.A. 1992, ApJ 392, 678
Moyes J. 1831 (Feb. 9, 1827), MNRAS 1, 1
O’Donoghue D., Charles P.A. 1996, MNRAS 282, 191
O’Donoghue D., et al. 1991, MNRAS 250, 363
Orosz J., et al. 1997, ApJ 478, L830
Ortolani S., et al. 1980, A&A 87, 31
Patterson J. 1998, PASP 110, 1132
Patterson J., et al. 1981, ApJ 248, 1067
Patterson J., et al. 1996, PASP 108, 748
Patterson J., et al. 1998, PASP 110, in press
Polidan R.S., Holberg J.B. 1987, MNRAS 225, 131
Press W.H., et al. 1992, in: Numerical Recipes 2nd ed., CUP
Priedhorsky W. 1986, A&SS 126, 89
Richter G.A. 1985, AN 307, 221
Richter G.A. 1992, in: Viña Del Mar Workshop on Cataclysmic Variable Stars, ASP Conf. Proc. 29, p. 12
Ritter H., Kolb U. 1998, A&AS 129, 83
Robertson J.W., Honeycutt R.K. 1996, AJ 112, 2248
Shahbaz T., Kuulkers E. 1998, MNRAS 295, L1
Tanaka Y., Lewin W.H.G. 1995, in: X-ray Binaries, CUP, p. 126
Udalski A. 1990, AJ 100, 226
van Paradijs J. 1983, A&A 125, L16
van Paradijs J., McClintock J.E. 1994, A&A 290, 133
van Paradijs J., Verbunt F. 1984, in: High Energy Transients, AIP Conf. Proc. 115, p. 49
Vogt N. 1980, A&A 88, 66
Vogt N. 1993, in: Cataclysmic Variables and Related Objects, Ann. Israel Phys. Soc. 10, p. 63
Warner B. 1995, in: Cataclysmic Variable Stars, CUP
Warner B. 1998, in: Wild Stars in the Old West, ASP Conf. Ser. 137, p. 2
White N.E., et al., 1984, in: High Energy Transients, AIP Conf. Proc. 115, p. 31
Whitehurst R. 1988, MNRAS 232, 35
Whitehurst R. 1994, MNRAS 266, 35
Whitehurst R., King A.R. 1991, MNRAS 249, 25