A 0620–00 revisited: a black-hole transient case-study

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Abstract

For the first time we have performed a detailed study of the X-ray, optical and infrared light curves and an intercomparison between these wavelengths (including radio) of the 1975/1976 outburst of the famous black-hole transient A 0620–00 (Nova Mon 1975, V616 Mon). We also investigated the optical behaviour up to a year after the main outburst. This study enabled us to find some new features, which have not been discussed before.

During the various stages of the outburst of A 0620–00 we found the X-rays lag the optical on the order of ~5 to ~20 days. Moreover, we found evidence that the activity associated with the secondary maximum started even earlier in the infrared. This suggests that most of the processes associated with the outburst occur in the outer parts of the accretion disk.

Although various drops in intensity (lasting on the order of a day or more) in the optical and X-ray outburst light curves of A 0620–00 have been reported before, we identified some new ones. One such X-ray ‘dip’ only appeared in the soft X-rays (1.5–6 keV) whereas at higher energies (>6 keV) the intensity slightly increases. This shows that the X-ray spectrum pivots near ~6 keV around that time. In the optical we found evidence for another local maximum around that time (so-called ‘intermediate’ maximum). The ‘intermediate’ maximum appears ~30 days after the secondary maximum, which is close to the viscous time scale of an irradiated accretion disk. We suggest this feature to be an ‘echo’ of the secondary maximum. At the end of the outburst another local maximum occurs. Since the time difference between the peak of the tertiary maximum and this local maximum is also on the order of the viscous time scale, we suggest that this feature is an ‘echo’ of the tertiary maximum. We find that drops in the optical and X-ray intensity before and during the rise to tertiary maximum are also present in various other short period soft X-ray transients (SXTs). They always occur ~150 days after the start of the outburst.

Although the X-ray spectrum of A 0620–00 gradually softens during the decay from outburst, we find for the first time that it starts to harden again ~100–150 days after the start of the outburst, similar to that seen in GS 2000+25 and GS 1124–68. This suggests we witness the transition from the so-called high to low state identified in black-hole X-ray binaries. We note that the time of spectral hardening in
A 0620–00, GS 2000+25 and GS 1124–68 is simultaneous with the occurrence of the drops in optical and X-ray intensity.

We also show that the optical outburst amplitude and the shape of the optical outburst light curve of A 0620–00 closely resembles those of the cataclysmic variable AL Com (where the compact star is a white dwarf). This strengthens the similarity in outburst and quiescent properties of the SXTs and ‘Tremendous Outburst Amplitude Dwarf novae’ (TOADs) or WZ Sge stars, and shows that in general the optical outburst light curves of both groups are governed by the disk properties and not by the compact object. Since irradiation provides a natural mechanism to prolong the outburst of SXTs, we suggest this could be of influence as well during TOAD outbursts.

Key words: Accretion, accretion disks, Binaries: close, Stars: individual (A 0620–00, V616 Mon), Novae, cataclysmic variables, X-rays: stars

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1 Introduction

In 1975 a powerful X-ray transient, A 0620–00, emerged in the constellation Monoceros (Elvis et al. 1975). A 0620–00 was the first X-ray transient to be identified with an optical brightening of a star, V616 Mon, at the same position (Boley & Wolfson 1975; Boley et al. 1976). It was therefore also designated as Nova Mon 1975. It is still the brightest extra-solar X-ray source seen to date, and many of the exciting results during the first months of its outburst were summarized by Maran (1976).

Because of its brightness the source has been studied in considerable detail at various wavelengths. The results have appeared in a large numbers of papers in the literature. There exists, however, no thorough comparison of the optical (UBV) light curves together with the X-ray light curves from various experiments. Either authors have presented (part of) the optical light curve (with sometimes the inclusion of data points from other observers) in one or two optical passbands and sometimes compared it with the X-ray light curve (e.g. Robertson, Warren & Bywater 1976; Shugarov 1976; Lloyd, Noble & Penston 1977; Ciatti, Mammano & Vittone 1977; Tsunemi, Matsuoka & Takagishi 1977; Chen, Livio & Gehrels 1993; Goranskii et al. 1996). The first

* This paper is dedicated to one of the discoverers of the optical counterpart of A 0620–00 (V616 Mon, Nova Mon 1975), Dr. Forrest Boley, who died on September 9, 1997.

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rough comparison of optical and X-ray light curves was undertaken by Whelan et al. (1977), together with a crude comparison with radio, infra-red and ultra-violet measurements.

Fortunately, almost all the optical (plus infra-red and ultra-violet) observations have been compiled by Ron Webbink in his unpublished report in 1978. In this report he showed (only) the overall B band light curve, and the corresponding B–V, and U–B measurements, whenever they were simultaneous. Subsequently, only a few authors have shown his B band light curve (e.g., Chevalier & Ilovaisky 1990; Van Paradijs & McClintock 1995). Since the outburst of A 0620−00 more (soft) X-ray transients (SXTs) have been identified, some of them with considerable optical coverage (see Chen, Shrader & Livio 1997). We note that most of these optical observations were only in one or two passbands, and so far A 0620−00 is still the only transient with a fairly complete optical light curve in more than 2 passbands (largely due to its brightness). Several of the X-ray transients have been either found to contain a black hole, including A 0620−00 (McClintock & Remillard 1986), or a neutron star (e.g. Van Paradijs 1998). Moreover, the comparison of the various outburst light curves (see White, Kaluzienski & Swank 1984; Van Paradijs & Verbunt 1984; Chen et al. 1993); Van Paradijs & McClintock 1995; Tanaka & Lewin 1995; Tanaka & Shibazaki 1996; Chen et al. 1997), and the short term (≤100 s) (X-ray) variability (e.g. Tanaka & Lewin 1995; van der Klis 1995) of the X-ray transients has led to a general picture of their behaviour, in which the main driver for these characteristics is the mass accretion rate through the accretion disk. Since no thorough study of the outburst light curve of A 0620−00 has been performed to date, and the fact that we can now place the results of its 1975/1976 outburst within the general framework of X-ray transient behaviour, we decided to perform, for the first time, an analysis of all the available optical, infra-red and X-ray light curves of A 0620−00 and undertake a detailed comparison between them.

In the next Sections we will first give an overview of what is already known of A 0620−00, then present the X-ray, optical and infra-red outburst light curves with newly identified features, and then compare it with behaviour seen in other X-ray transients. Finally, we will compare the properties of A 0620−00 with a special unstable class of the cataclysmic variables, i.e., the ‘Tremendous Outburst Amplitude Dwarf novae’ (TOADs), or the WZ Sge stars.
2 A 0620−00 revisited

2.1 Outburst

A 0620−00 was discovered by the Sky Survey Experiment on board Ariel V on August 3, 1975 (Elvis et al. 1975). Subsequently, after a more precise location became available from SAS-3 (Doxsey et al. 1976), the source was detected in the radio (e.g. Owen et al. 1976), optical (Boley et al. 1976) and infra-red (e.g. Kleinmann, Brecher & Ingham 1976). The reason why A 0620−00 was so bright during outburst is its proximity, with an estimated distance of \( \sim 1 \) kpc (see e.g. Shahbaz, Naylor & Charles 1994).

During the rise to X-ray maximum a precursor was seen. The maximum of the X-ray outburst was reached within a week after the precursor (Elvis et al. 1975). The subsequent decay was approximately exponential with a decay time scale of \( \sim 29 \) days up to the beginning of October (Kaluzienski et al. 1977; Pounds et al. 1977). About one and a half months after X-ray maximum the decay halted for \( \sim 10 \) days during which the intensity slightly increased (Carpenter et al. 1976; Matilsky et al. 1976; Kaluzienski et al. 1977); this period is called a ‘glitch’ or secondary maximum in the decay light curve (see e.g. Chen et al. 1997). Thereafter the exponential decay resumed again with a time scale of \( \sim 20 \) days (Kaluzienski et al. 1977; Pounds et al. 1977), until the beginning of 1976 when the outburst light curve flattened. At the end of 1976 January the X-ray flux increased again for about a month, and subsequently faded rapidly with a decay time scale of less than \( \sim 10 \) days to below detection limits (Kaluzienski et al. 1976; 1977). This last episode showed up as a large ‘bump’ or a broad (tertiary) maximum at the end of the outburst light curve.

In the radio A 0620−00 was only active for a few weeks (e.g. Davis et al. 1975; see also Hjellming et al. 1988). The radio decay time was \( \sim 5 \) days (Davis et al. 1975).

In the optical, A 0620−00 faded from maximum less fast than in X-rays by about 0.015 magnitude per day, corresponding to a decay time scale of \( \sim 67 \) days (Duerbeck & Walter 1976; Whelan et al. 1977; Lloyd et al. 1977; Pounds et al. 1977; see also Tsunemi et al. 1977; Goranskii et al. 1996). The glitch also showed up in the optical, at approximately the same time as in X-rays (e.g. Kaluzienski et al. 1977; Whelan et al. 1977; Tsunemi et al. 1977; see also Chen et al. 1993). A large bump could also be seen at the end of the optical outburst light curve (e.g. Lloyd et al. 1977; Whelan et al. 1977; Tsunemi et al. 1977), but this time the optical rose before the X-ray did (e.g. Chen et al. 1993). The final optical decay started about \( \sim 2 \) weeks later than the final X-ray decay, and had a fast decay time scale of \( \sim 12 \) days (Tsunemi
et al. 1977). UBV measurements during the final decay showed B−V already near its quiescent value, whereas U−B was still at its outburst value (Lyutyi 1976; see also Lyutyi & Shugarov 1979).

A ∼3.9 day modulation in the optical UBV was reported during the first part of the decay up to the glitch (Duerbeck & Walter 1976). However, a modulation on a time-scale of ∼8–10 days just after the first glitch, was reported by Chevalier et al. (1980). Moreover, Tsunemi et al. (1977) reported an optical period of ∼7.4 days from the three months during the decay. Subsequent reanalysis of the data of Duerbeck & Walter (1976) did not reproduce the ∼3.9 day period (Matilsky et al. 1976; Chevalier et al. 1980; see also Tsunemi et al. 1977). Minima in the optical light curve below the extrapolated general decay (Lloyd et al. 1977, Robertson et al. 1976) and an eclipse-like feature near the end of the outburst (Chevalier et al. 1980) were consistent with the ∼7.4 day variability.

In X-rays a period of ∼7.5 days during the main decay and ∼7.8 days during the ‘trough’ before the broad tertiary maximum plus initial rise to the tertiary maximum was found in SAS-3 data (Matilsky et al. 1976). A reanalysis of the SAS-3 data, however, did not reveal the variability in the earlier phase of the decline, but rather a smooth exponential decay; the ∼7.8 days variability was confirmed (Plaks 1991). Intensity minima found in the overall light curve of the various Ariel V instruments (Pounds et al. 1977; see Watson 1982) are related to the 7.8-day cycle. The amplitude of the modulation is largest when A 0620−00 is weakest (Matilsky et al. 1976; Pounds et al. 1977). It was recognized by Tsunemi et al. (1977) that the optical 7.8-day modulation was not in phase with that in X-rays; the X-rays were reported to precede the optical by about one day (Chevalier et al. 1980).

During the outburst the optical revealed B−V and U−B colours very similar to Sco X-1 and Cyg X-2 (e.g. Eachus, Wright & Liller 1976; Matsuoka & Tsunemi 1976). Also the optical spectra at outburst maximum were similar to Sco X-1, showing evidence for X-ray heating effects. However, the emission features of Hα and Hβ were more like dwarf novae in outburst (Whelan et al. 1977). During the maximum and initial decline phase the ratio of the X-ray to optical luminosity was ∼1000, again showing the similarity to Sco X-1 (Boley et al. 1976; Whelan et al. 1977; Matilsky et al. 1976; Kaluzienski et al. 1977; see also Tsunemi et al. 1977).

The X-ray spectral behaviour of A 0620−00 was that of a typical X-ray transient (see e.g. Tanaka & Lewin 1995; Tanaka & Shibazaki 1996). Before the precursor the spectrum was hard, whereas during the subsequent rise to maximum the spectrum rapidly softened (Ricketts, Pounds & Turner 1975; Matilsky et al. 1976); the X-ray flux above ∼10 keV actually fell during that period (Ricketts et al. 1975). Near X-ray maximum there was evidence for a hard
component above $\sim 15$ keV (Ricketts et al. 1975; see also White et al. 1984), and possibly even above $\sim 30$ keV (Coe, Engel & Quenby 1976). During the main decay the spectral hardness gradually declined (Matilsky et al. 1976, Carpenter et al. 1976). Two months after X-ray maximum Coe et al. (1976) reported spectral hardening (up to $\sim 200$ keV) with respect to their measurement near X-ray maximum. However, as already noted by e.g. Tanaka & Lewin (1995), their measurements are very marginal. In fact, a study of the high energy range up to $\sim 56$ keV, as measured with SAS-3 nearly simultaneously with the measurements by Coe et al. (1976), did not reveal evidence for such a hard power-law tail (Hwang 1988).

On short timescales (from hours down to msec) A 0620$-$00 was very quiet during its outburst. No modulation larger than $\sim 3\%$ over timescales 200 s–2 d was seen during the rise and at maximum (Ariel V SSE, 2–18 keV, Elvis et al. 1975). Near X-ray maximum also down to 0.2 msec no evidence for pulsations were reported (SAS-3 slat collimator system, 1.5–60 keV, Doxsey et al. 1976). During the first months after maximum there was no evidence for periodic fluctuations or the shot noise variability seen in e.g. Sco X-1 (Ariel V RMC, 3–8 keV, Carpenter et al. 1976). Measurements by the medium X-ray energy detector (1–8 keV) on board the Astronomical Netherlands Satellite (ANS) during the glitch also revealed no indications of periodic variations between 0.25 and 100 s (Brinkman et al. 1976). The high count rates observed with the various X-ray detectors from A 0620$-$00 would have definitely revealed any variability similar to that seen in the low state or very high state of black-hole candidates (e.g. van der Klis 1995, and references therein). Since none were reported and from the fact that the X-ray spectrum was very soft, White et al. (1984) already concluded that A 0620$-$00 was most probably in its high state during most of the observations. We note that this is consistent with the behaviour of A 0620$-$00 with respect to other SXTs in the hard (20–200 keV) versus soft (1–20 keV) X-ray luminosity study of Barret, McClintock & Grindlay (1996). The spectral changes during the rise of the outburst may have indicated a change from the low to a high state (White et al. 1984).

Optical observations just after the glitch on 1975 October 10 showed no random variations with amplitudes larger than 0.01 magnitudes between 2 and 200 sec (Robinson & Nather 1975). Also during several nights in March 1976 (i.e. during the large bump at the end of the outburst) no optical flickering activity was found down to $\sim 2$ s (Chevalier et al. 1980).

2.2 Quiescence

Soon after the first optical detection of A 0620$-$00, the quiescent optical star (V616 Mon) was found on archival photographic plates at a magnitude of
B_{pg} \sim 20.0-20.5 \text{ (Ward et al. 1975; Eachus et al. 1976). Together with the magnitude near optical maximum this led to a large outburst amplitude of } \sim 9 \text{ mag. Even earlier photographic plates revealed the existence of a previous outburst of A0620–00 at the end of 1917 (Eachus et al. 1976), suggesting an outburst recurrence time of } \sim 60 \text{ years.}

A0620–00 was quickly recognized to have a binary nature, most probably related to dwarf novae. Based on its transient nature and its brightness in X-rays it was suggested that A0620–00 contained a neutron star or a black hole instead of a white dwarf (e.g. Elvis et al. 1975; Avni, Fabian & Pringle 1976). From photometric colours in quiescence (using plates taken before the 1975/1976 outburst) Ward et al. (1975) suggested the companion star to be a red dwarf, most likely a K star. Subsequently, it was spectroscopically identified as a K5V star (Oke 1977; McClintock et al. 1983; see also Murdin et al. 1980).

It was suggested that if the companion star was a red dwarf its orbital period would be \sim 8 \text{ hr (Avni et al. 1976). When A0620–00 had reached quiescence, the search for its orbital period was started. It was finally established to be } \sim 7.75 \text{ hr (McClintock et al. 1983; McClintock & Remillard 1986).}

The first dynamical evidence for the compact star being a black hole came from the work of McClintock & Remillard (1986). They found a compact star mass of M_X > 3.2 M_\odot, with a most likely value of \sim 7 M_\odot. By measuring the rotational broadening of the absorption line spectrum the mass ratio^2, was found to be \sim 0.07 (Marsh, Robinson & Wood 1994). Finally, the analysis of ellipsoidal variations in the infra-red light curves revealed the inclination to be \sim 37^\circ, which therefore implied the mass of the compact star and the companion star to be M_X \sim 10 M_\odot and M_{opt} \sim 0.6 M_\odot, respectively (Shahbaz et al. 1994). We note that the quiescent BV light curves are somewhat more complex (see also Sect. 5.4.1), and that their irregularities have been interpreted as a grazing eclipse of the companion star by the accretion disk; this would imply inclinations of \text{i} > 62^\circ (Haswell et al. 1993).

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^2 \text{ Mass ratio } q \equiv M_{opt}/M_X, \text{ where } M_{opt} \text{ and } M_X \text{ are the mass of the companion star and compact object, respectively.}
3 Observations

3.1 X-ray

The X-ray outburst light curves shown in this paper are those from instruments on board SAS-3 and Ariel V. Data from the SAS-3 Center Slat collimator (CSL) provided information in four energy channels (CSL A–D) from 1.5–60 keV (Buff et al. 1977). Parts of these data have been reported by Doxsey et al. (1976), Matilsky et al. (1976) and Plaks (1991). We used the data as re-analysed by Plaks (1991), i.e. data from the two argon channels, 1.5–6 keV and 6–15 keV, and data from the first xenon channel, 10–42 keV.

The Ariel V instruments from which we have used data are the Sky Survey Experiment (SSE, also named as Sky Survey Instrument or SSI), the All Sky Monitor (ASM), and the Rotation Modulation Collimator (RMC). The SSE provided count rates in eight channels covering 2–18 keV (Villa et al. 1976). We used the lightcurve from all eight channels combined as presented by Elvis et al. (1975; see also Chen et al. 1997) and Watson (1982). The ASM data are those presented by Kaluzienski et al. (1977; see also Chen et al. 1997) and give the count rate in one 3–6 keV energy band (Holt 1976). The RMC provided data in three energy channels, i.e. 3.0–4.3 keV, 2.3–5.9 keV and 4.9–7.6 keV. We used the data in the combined 3–7.6 keV energy band, as presented by Carpenter et al. (1976). A composite outburst light curve of all the Ariel V SSE, ASM, and RMC data, together with the SAS-3 coverage was given by Watson (1982). We note that more sketchy overall X-ray outburst light curves have been given by Carpenter et al. (1976) and White et al. (1984).

3.2 Optical

Almost all of the optical data presented in this paper come from the compilation by Webbink (1978). They include all photoelectric, photographic, and visual observations appearing in the published literature available to him, and many unpublished observations communicated to him, up to the beginning of 1977. Observations noted as uncertain, doubtful, or erroneous (see Webbink 1978) have not been taken into account in this paper. We also did not use the data by Tsunemi et al. (1977), since their measurements are known to have systematic differences with respect to the other B band data (see Tsunemi et al. 1977). From our analysis we find that this also applies to the photographic B measurements of Matsuoka & Tsunemi (1976). In addition we used the data obtained during outburst as reported by Hudec (Bpg, 1977), Borisov, Derevyashkin & Deych (Bpg, 1977) and Chevalier et al. (UBV, 1980),
and the data obtained in quiescence up to $\sim 1$ year after the final decay from the outburst as reported by Lyutyi & Shugarov ($V_{pg}$, 1979) and Kurochkin, Karitskaya & Bochkarev ($B_{pg}$, 1988).

Apart from the photographic B and V plates obtained with the 26- and 13-inch reflectors of the Royal Greenwich Observatory during the period 1975 August 27 and 1976 April 4 at Herstmonceux (Lloyd et al. 1977), there were 2 additional photographic B plates which have not been reported before. They were taken with the 26-inch reflector on 1976 October 21 (03:29 UT) and October 22 (02:56 UT). At both times the optical star was not visible, resulting in upper limits of $B_{pg} \sim 16.5$ and $B_{pg} \sim 15.0$, respectively (Argyle 1997, private communication).

The visual measurements of observers of the Variable Star Observers League in Japan (VSOLJ) were not available in Webbink’s (1978) compilation, and we have therefore included them in our analysis. We also used additional visual measurements (mainly upper limits) after the final decline from outburst by observers from the American Association of Variable Star Observers (AAVSO, Mattei 1997), the Variable Star Section of the Royal Astronomical Society of New Zealand (VSS RAS NZ), and the Association Francaise des Observateurs d’Etoiles Variables (AFOEV).

The uncertainties in the photoelectric UBV observations during outburst were typically $\sim 0.01–0.03$, mainly depending on the brightness of A 0620−00 and the observed wavelength band (see Duerbeck & Walter 1976, Robertson et al. 1976; Lyutyi 1976; Chevalier et al. 1980). During the final decline to quiescence this uncertainty increased to $\sim 0.05–0.1$, depending on the wavelength band (Lyutyi 1976). The uncertainties in the photographic BV observations during outburst were typically $\sim 0.07–0.1$ (e.g. Lloyd et al. 1977), and sometimes $\sim 0.1–0.2$ (Hudec 1977), depending on the instrument used. In quiescence the typical uncertainties were $\sim 0.1–0.4$ for the photoelectric UBV observations, depending on the instrument used and the wavelength band (see Ciatti et al. 1977; Lyutyi & Shugarov 1979), and $\sim 0.2–0.5$ for the photographic BV observations (Lyutyi & Shugarov 1979; Kurochkin et al. 1988). The visual estimates had usual uncertainties of $\sim 0.1$ during outburst for one observer. However, the systematic uncertainties between different observers are larger mainly because of the differences in the observers themselves, the inadequacy of finding charts used at that time and the systematic errors in the magnitudes of comparison stars.
4 Results

4.1 Outburst

4.1.1 X-ray behaviour

In Fig. 1 we show the X-ray outburst light curves of of A 0620−00 obtained with four instruments, i.e., the SAS-3 CSL-A (1.5–6 keV), and the Ariel V SSE (2–18 keV), ASM (3–6 keV) and RMC (3–7.6 keV). In Fig. 2a we show the SAS-3 CSL-A data again, together with CSL-B (6–15 keV) and CSL-C (10–42 keV) data. Clearly, the light curves show the fast rise to maximum, the exponential decay for \(\sim 45\) days, the secondary maximum \(\sim 60\) days after the start of the outburst followed by a faster exponential decay with respect to the first part, the \(\sim 7.8\) day oscillations during the trough, the broad tertiary maximum \(\sim 200\) days after start of the outburst and the final fast decay to below the detection limits.

The maximum of the precursor in the Ariel V SSE light curve was at JD 2442631 (Elvis et al. 1975; see also Fig. 5a). We note that this feature could also represent a drop in intensity (similar to that seen later in the outburst, see below), with a minimum at JD 2442631.4 and a duration of about a day. The maximum of the outburst was reached near JD 2442637 (see Elvis et al. 1975; Doxsey et al. 1976), whereas the secondary maximum peaked near JD 2442692 (see Matilsky et al. 1976, see also Fig. 5b). During the first and second exponential decays the source slowly softened as can be seen in Fig. 2b where we plot the hardness ratio using the SAS-3 CSL-A and CSL-B detectors (see also Matilsky et al. 1976; Plaks 1991).

In Fig. 1 we also show the result of an exponential fit to part of the first exponential decline (JD 2442658–JD 2442682) of the Ariel V ASM light curve and its extrapolation to the beginning and the end of the outburst. A qualitatively similar fit is obtained from the same stage of the SAS-3 CSL-A light curve (see Fig. 5b). As can be seen, the secondary and tertiary maxima are enhancements in the lightcurve; the X-ray intensity seems to always return to the extrapolated level expected from the first exponential decay. The drops in intensity related to the \(\sim 7.8\) day oscillations occur below the first exponential decay curve.

We also fitted the first 100 days of the SAS-3 CSL-A outburst light curve with the model of Augusteijn, Kuulkers & Shaham (1993), in order to determine when the tertiary and subsequent maxima are expected in their model. The data is best fit with the following parameters (see Augusteijn et al. [1993] for a description of these parameters): \(\gamma^{-1} = 26\) days, \(\beta^{-1} = 2.1\) days, \(T = 49\) days and \(\alpha\psi = 0.16\); the fit is shown in Fig. 1. Note that \(\gamma^{-1}\), \(\beta^{-1}\) and \(\alpha\psi\) are...
Fig. 1. * X-ray outburst light curves of A0620−00 as obtained with (from top to bottom) the SAS-3 CSL-A (1.5–6 keV), and the Ariel V SSE (2–18 keV), ASM (3–6 keV) and RMC (3–7.6 keV) instruments. The units of the SAS-3 CSL-A and the Ariel V RMC data are cts s$^{-1}$, whereas that of the Ariel V SSE and ASM are given in units of the Crab count rate (in the corresponding energy bands). Note that the Ariel V SSE has been shifted by a factor of 40 and the RMC data by a factor of 0.002. Error bars on each measurement are given for all data of the SAS-3 CSL-A and Ariel V ASM instruments, whereas for the Ariel V SSE typical error bars are given at the beginning of the outburst and near the maximum (see Elvis et al. 1975); when no errors are plotted for the Ariel V RMC data, they are less than 10% (see Carpenter et al. 1976). For the first $\sim$110 days of the SAS-3 CSL-A light curve we show the corresponding fit to the model of Augusteijn, Kuulkers & Shaham (1993, see text for parameters), while for the Ariel V ASM we show the fit to part of the first exponential decline (JD 2442658–JD 2442682) and its extrapolation to the beginning and the end of the outburst.
Fig. 2. a. X-ray outburst light curves of A 0620−00 as obtained with (from top to bottom) the SAS-3 CSL-A (1.5–6 keV), CSL-B (6–15 keV) and CSL-C (10–42 keV) detectors. The CSL-C light curve has been offset by a factor of 1/30 for clarity. b. Hardness light curve of A 0620−00. Hardness is defined as the ratio of the count rates from the CSL-B and the CSL-A detector. Note the clear hardening after JD 24462732.

comparable to those found for GS 2000+25 (Augusteijn et al. 1993). Extrapolating the fit gives the following times of the expected tertiary, quaternary and quinternary maxima: ∼JD 2442739, ∼JD 2442792 and ∼JD 2442842, respectively.

Carpenter et al. (1976) noted flaring in the Ariel V RMC light curve near JD 2442643. This is consistent with the Ariel V ASM measurements at JD 2442644–645 which lie above that expected from a pure exponential decay of the data between JD 2442658 and the secondary maximum (Kaluzienski et al. 1977; see also Fig. 5a). This may be due to a small bump in the light curve just after maximum, as sketched in the composite light curves by Carpenter et al.
Fig. 3. Blow-up of the $SAS-3$ CSL-A (a.) and CSL-B (b.) light curves around the time of the drop in intensity ($\sim$JD 2446715) in the $SAS-3$ CSL-A light curve.

(1976) and White et al. (1984). Fig. 2a reveals that the pure exponential decay started somewhat later at higher ($\gtrsim$6 keV) energies, which may indicate that the bump is more pronounced at these higher energies.

The Ariel V RMC light curve shows a small glitch in its light curve near JD 2442654, as noted by Carpenter et al. (1976) and Pounds et al. (1977). This cannot be seen in the $SAS-3$ CSL-A and CSL-B light curves. We note that the $SAS-3$ CSL-A data as presented by Matilsky et al. (1976) also showed an erratic decay up to the secondary maximum, but this has been calibrated out in the improved analysis by Plaks (1991), which is shown here. So, whether the small glitch in the Ariel V RMC light curve is real or due to systematics in the data analysis is not clear.

A small sharp dip in the Ariel V SSE light curve was noted by Pounds et al. (1977) with a minimum near JD 24462730.8 (see also Fig. 5b) and lasted for about 2 days. Another small sharp dip, which has not been noted before, can be seen in the $SAS-3$ CSL-A light curve which is in progress near JD 2446714.5 and lasted for at least a day (see Fig. 3 for a blow-up of the $SAS-3$ CSL-A and $SAS-3$ CSL-B lightcurves). This dip occurs within the uncertainties of the Ariel V ASM light curve. At higher energies ($\gtrsim$6 keV), however, the $SAS-3$ CSL-B (Fig. 3) and CSL-C light curves (Fig. 2a) are more or less flat just before the dip and show a small increase, instead of a dip, which causes a small increase of the hardness during that time (Fig. 2b). This means that during that time the X-ray spectrum pivoted near 6 keV with the low energy count rate decreasing, while the high energy count rate was increasing.
Whereas the SAS-3 CSL-A count rate gradually decreased from the secondary maximum until ∼2442780, the SAS-3 CSL-B clearly shows a higher count rate than that extrapolated from the exponential decay after the secondary maximum. The SAS-3 CSL-B intensity is consistent with being constant between JD 24462747 and JD 24462797. This results in a clear hardening of the source (Fig. 2b; see also Plaks 1991) which has not been noted before. The hardening started somewhere between JD 24462732 and JD 24462747. Note that the expected time of the tertiary maximum in the model of Augusteijn et al. (1993), i.e. JD 24462739, lies within this range.

As noted by Kaluzienski et al. (1977) and Pounds et al. (1977) the minima in the Ariel V SSE and ASM light curves between JD 2442772 and JD 2442807 correspond to the minima which occur in the SAS-3 CSL-A light curve. Note that the minima in the Ariel V SSE light curve appear to be broader than those in the SAS-3 CSL-A light curve. This is solely due to the sampling (see Watson 1982) of the Ariel V SSE data at intervals of a few days during the trough. We note that short sharp decreases in the Ariel V ASM light curves also appear near JD 2442758, JD 2442814 and JD 2442854 (see also Fig. 5d).

The broad tertiary maximum peaked around JD 2442836 (see also Fig. 5d). After JD 2442859 A 0620−00 disappeared below the Ariel V ASM instrument threshold (Kaluzienski et al. 1977).

4.1.2 X-ray versus other wavelengths

In Fig. 4 we present the outburst of A 0620−00 viewed over all wavelengths. This figure shows the optical (UBV) light curves, together with the X-ray outburst light curve from Ariel V ASM data and part (up to JD 24462641) of the Ariel V SSE data. For reference we also give the radio light curve at 962 MHz as presented by Davis et al. (1975), and at the top of the figure we have indicated the observation times of the ANS ultra-violet experiment (see Wu et al. 1976; 1983). The radio outburst is clearly very short, i.e. a couple of weeks (see also Fig. 5a). The ultra-violet observations by Wu et al. (1976, near JD 2442685) were obtained just at the beginning of the secondary maximum, whereas those reported by Wu et al. (1983, near JD 2442864) were obtained during the first part of the final decay to quiescence (about a week after the source dropped below the detection limits of the Ariel V ASM3). We note that Tsunemi et al. (1977) found that the very first decay seemed to be more rapid (∼0.018 mag per day) than the rest of the main decay. Our data cover the same time base as theirs; we found, however, no clear evidence for different decay rates.

3 Kaluzienski et al. (1976) reported an upper limit of ∼0.04 Crab near JD 2442864.5 over a 0.5 day integration period.
Fig. 4. Overall outburst light curve in the optical (photographic and photoelectric UBV data) and X-ray (Ariel V ASM and part of the SSE data) of A 0620−00. The SSE light curve has been scaled (by a factor of 2.1) to match the exponential decay of the first ~50 days of the ASM light curve. For reference we also included the radio light curve; the times of the ANS ultra-violet observations are indicated at the top.

In Fig. 5a we zoom in on the first ~50 days of the outburst. As noted in the previous section, the X-ray maximum of the outburst was reached near JD 2442638. From synchrotron radio source model fits (Fig. 5a; see Hjellming et al. 1988; Hjellming & Han 1995) a maximum near JD 2442642 is derived for the 962 MHz radio data, while it is estimated to be ~JD2442641 and ~JD2442639.5 for data at 1.4 GHz and 2.7 GHz, respectively. Although this suggests that the radio outburst was delayed with respect to the X-ray outburst, it is clear that the radio data are consistent with only a decay and that the maximum could have occurred earlier. It may be worthwhile to note that the expected start of the radio outburst in the synchrotron radio source model fit is ~2442632, i.e. very close to the time of the precursor in the Ariel V SSE data.

The optical counterpart of A 0620−00 was discovered by Boley et al. (1976) in the early morning of August 16 (JD 2442641). Their measurements on this
day and the following two days revealed the object to be of magnitude 12 or brighter. Since these measurements may give us an estimate of when the optical maximum was reached, we decided to study these observations more carefully. We note that Ciatti et al. (1977) estimated the optical maximum to be near JD 2442650, but they used a ∼12th magnitude estimate by Boley et al. (1976).

The observing conditions were very bad (it was ∼20 min before sunrise) and the telescope drive was not functioning in the contorted position Boley and Wolfson had to get it into (Wolfson, 1997, private communication; see also Boley et al. 1976). But, examining their discovery image, an image tube photograph (Boley et al. 1976), one can still get a rough estimate of the actual magnitude during the discovery. Comparing the magnitudes of the comparison stars in the frame with those reported by Webbink (1978) one deduces that the image tube must correspond more closely to V band than the B band. By comparing the brightness of A 0620−00 with that of four comparison stars, one can derive $V = 11.30 \pm 0.17$ mag, where the error is a standard deviation from estimates with respect to four comparison stars (Webbink 1997, private communication).

The estimate of the Boley et al. (1976) observation is also plotted in Fig. 5a, together with the expected value (11.02±0.03) as extrapolated from a linear fit to the first decay phase in the V band. Within the uncertainties, the observed and expected magnitudes do not match. We note, however, that the bright sky and the high airmass also affects our estimate from the Boley et al. (1976) observation and therefore its uncertainty may be even larger. We cannot therefore say with certainty if the optical maximum was reached between Boley et al.’s observation (∼JD 2442641) and the start of the V band measurements (∼JD 2442648), or e.g. that near maximum the optical shows a plateau. If the former is true, then optical maximum was reached after the X-rays reached its maximum. In the latter case, the maximum would have been reached before ∼JD 2442641. The B measurements start about one day earlier than the V band measurements and do not show evidence for flattening. Also, a visual estimate at JD 2442645.6 by Locher (1975) of $V \sim 10.4$ is available (see also Fig. 8); this estimate is, however, far from both the estimate of Boley et al.’s observation and that expected from extrapolation from the first exponential decay in V, and we suspect therefore that Locher’s measurement has been affected by systematic errors in the magnitudes of comparison stars (Section 3.2).

Near the time of the X-ray secondary maximum, there is also a secondary maximum in the UBV outburst light curve (Figs. 4 and 5b). The rise to secondary maximum starts more or less simultaneously in the optical and X-ray (see also Section 4.1.3). However, the optical peak was reached near JD 2442687, whereas in X-rays it was reached near JD 2442692 (Section 4.1.1).
Fig. 5. *

a. The first $\sim50$ days of the outburst of A 0620−00. Shown are the V band, Ariel V SSE and ASM, SAS-3 CSL-A data, and the radio measurements. The Ariel V SSE and ASM light curves have been scaled to match the SAS-3 CSL-A light curve. Plotted is also the optical estimate of A 0620−00 during the optical discovery observation (○), and the expected value as extrapolated from the fit to the V band data (●). For the units of the radio data we refer to Fig. 4. Shown are the linear fit to the V band data between $\sim$JD 2442648 and $\sim$JD 2442682, the exponential fit to part of the first exponential decline (JD 2442658–JD 2442682) of Ariel V ASM data and its extrapolation to the beginning and the end of the outburst, and the synchroton radio source model fit to the radio data by Hjellming et al. (1988). b. The exponential decay phase of the outburst of A 0620−00. Shown are the U band measurements, and the X-ray (Ariel V SSE and SAS-3 CSL-A) data. The Ariel V SSE has been shifted to match the SAS-3 CSL-A light curve. The arrows indicate the times of the dips in the X-ray light curve. Fits to the first exponential decay in the U band and SAS-3 CSL-A X-ray light curve and their extrapolation are plotted as dotted lines. c. The light curve during the trough of the outburst of A 0620−00. Shown are the B band measurements and the SAS-3 CSL-A data. d. The light curve at the end of the outburst of A 0620−00. Shown are the B band measurements and the Ariel V ASM data. Symbols in the four figures are similar to those used in Figs. 1 and 4.
This suggests a delay in X-rays with respect to the optical of \(\sim 5\) days.

The second exponential decay phase in X-rays is faster than the first exponential decay phase (Section 4.1.1) and seems to be rather smooth before and after the secondary maximum. The second exponential decay in the U band is even faster (see Fig. 5b), and therefore the optical catches up with that expected from the first exponential decay earlier with respect to that in X-rays (see also Section 4.1.3).

About 30 days after the secondary maximum the optical UBV shows another local maximum (possibly preceded by a depression), which is not seen in the X-ray light curve. It is clearly visible in the U band data (Fig. 5b). This feature in the light curve is the modulation reported by Chevalier et al. (1980); we will denote this as an ‘intermediate maximum’. The depression just before the peak of the ‘intermediate maximum’ occurs exactly at the same time as the small X-ray dip in the SAS-3 CSL-A light curve. Unfortunately, no simultaneous optical data are available during the other small X-ray dip, near JD 24462731 as observed with the Ariel V SSE (Section 4.1.1).

Two minima during the trough in the B and V light curve (Fig. 4) are seen near JD 2442771 and JD 2442796 (see also Robertson et al. 1976). In Fig. 5c we zoom in on the trough of the outburst, just before the large bump at the end of the outburst light curve. The \(\sim 7.8\) day X-ray oscillations are clearly visible. The optical also shows evidence for minima and maxima during the same part of the outburst and are most probably related to the X-ray oscillations (see already Section 2). Fig. 5c shows clearly that the optical and X-ray are almost anti-correlated, as can especially be seen between \(\sim\) JD 2442790 and \(\sim\) JD 2442797. If the optical tracks the X-rays, this means that the X-rays are delayed by \(\sim 4.5\) days with respect to the optical or that the optical is delayed by \(\sim 4\) days with respect to the X-rays.

The large bump at the end of the light curve is broader in the optical compared to the X-rays. As can be seen in Fig. 5d and shown by Chen et al. (1993), the broad tertiary maximum started probably earlier by about \(\sim 15\) days in the optical than in X-rays. Also, the peak of the optical tertiary maximum was reached somewhere between \(\sim\) JD 2442816 and \(\sim\) JD 2442827. In X-rays this peak was reached around JD 2442836 (Section 4.1.1), suggesting a delay between the optical and X-ray peak of \(\sim 10–20\) days. At the end of the outburst, just before the final decay, there is a dip followed by an increase in brightness of \(\sim 0.5\) magnitudes, resulting in another intermediate maximum (at \(\sim\) JD 2442853), in the optical light curve. This is the ‘eclipse-like feature’ of Chevalier et al. (1980), see Section 2. The Ariel V ASM light curve shows evidence for a similar kind of dip: at the end of the X-ray decay A0620−00 rises above the detection limits near JD 2442855 and drops below the detection limits again \(\sim 4\) days later. If this so-called ‘hiccup’ in X-rays is related
Fig. 6. Infrared measurements (I\textsubscript{ck} and K, see text) during the A 0620−00 outburst. For comparison we also show the V band data shifted by 3 magnitudes. Errors on the I\textsubscript{ck} have not been given in the literature.

to that in the optical, it also suggests a delay between the optical and X-ray of ∼5 days.

4.1.3 Infrared

In Fig. 6 we show the Cape-Kron I (I\textsubscript{ck}, Robertson et al. 1976) and K band (Jameson 1975; Kleinmann et al. 1976; Citterio et al. 1976; Szkody 1977) measurements during the outburst of A 0620−00, together with the V band light curve (shifted by 3 magnitudes). Data at other infrared wavelengths are available (e.g. R\textsubscript{ck}, J, and H), but we did not plot them, since their number of measurements is less than that of I\textsubscript{ck} and K band data, and do not reveal additional information.

The K band measurements between JD 2442680 and JD 2442690 show some variations in excess of that expected from a smooth decay, which is near the optical (and X-ray) secondary maximum. We note that the K band measurement near JD 2442680 lies above that expected, assuming a decay rate similar to the V band measurements from the beginning of the outburst. Similarly, the I\textsubscript{ck} measurement near JD 2442682 lies higher than expected from a smooth decay with a rate similar to the V band. From the optical data we infer that
the rise to secondary maximum starts between JD 2442685 and JD 2442687; whereas this occurs near JD 2442684 for the X-rays. This may indicate that in the infrared activity already started before that in the optical and X-rays.

As already noted by (Citterio et al. 1976) the two K band measurements near JD 2442716 show evidence for a sudden increase in the K band magnitude within a day. This occurs exactly near the time of the ‘intermediate maximum’ (see Section 4.1.2). We note, however, that their simultaneous H band measurements did not show significant changes.

During the trough of the outburst the I_{K2} measurements follow the behaviour seen in the V band.

From Fig. 6 it also becomes clear that in the V band the secondary maximum near JD 2442687 and the intermediate maximum near JD 2442716 are much shorter lived than the secondary maximum in X-rays (Section 4.1.1), i.e. within \( \sim 5 \) days the V band follows again the decay as extrapolated from the first exponential decay.

### 4.1.4 Optical colour behaviour

Following Webbink (1978), but now with additional data, we plot the B magnitude during the outburst, together with the photoelectric B–V and U–B measurements. We have also plotted the linear fits to the B–V and U–B data in order to clarify changes in these measurements. Lloyd et al. (1977, nearly simultaneously photographic BV data) and Lyutyi (1976, simultaneous photoelectric BV) concluded from their data sets that B–V stayed roughly constant during the whole outburst. The same was concluded for the photoelectric U–B measurements by Lyutyi (1976). Duerbeck & Walter (1976), however, reported a slight enhancement in the photoelectric B–V and U–B measurements during the first exponential decay. The fit shows that, apart from small deviations, B–V slowly increased from \( \sim 0.22 \) to \( \sim 0.31 \) from the beginning of the outburst to just before the final decline. The change in U–B is larger; it increased from about \( -0.79 \) in the beginning of the outburst to about \( -0.56 \) just before the final decline. Deviations in B–V and U–B occur between \( \sim \) JD 2442684 and JD 2442700 (i.e. during the secondary maximum), after \( \sim \) JD 2442718 (just after the ‘intermediate maximum’), during the trough near \( \sim \) JD 2442795 (see also Robertson et al. 1976), and at the end of the tertiary maximum, i.e. around \( \sim \) JD 2442850 (near the ‘eclipse-like feature’).

At the final decline to quiescence photoelectric UBV measurements revealed a different behaviour as compared to the rest of the outburst (see Lyutyi 1976; Lyutyi & Shugarov 1979): between JD 2442856.5 and JD 2442869.3 B–V was already close to its quiescent value (\( \sim 1.3 \), e.g. Murdin et al. 1980), while U–B was still at an outburst value of \( \sim -0.76 \) (quiescence \( U-B \) is \( \sim 0.5 \), e.g. Lyutyi
Fig. 7. a. Photoelectric (●) and photographic (○) B magnitude measurements during the outburst of A 0620−00. For reference we give the Ariel V SSE and ASM outburst light curve (see also Fig. 4). Photoelectric B−V (b.) and U−B (c.) measurements of A 0620−00. & Shugarov 1979). This indicates that in U and B the flux dropped faster to quiescence than in V, as can be seen in Fig. 4.

4.2 Quiescence

Extensive optical monitoring of the SXT GROJ0422+32 (X-ray Nova Per 1992, V518 Per) after the main outburst has led to the detection of ‘mini-outbursts’ or rebrightenings (Callanan et al. 1995; Chevalier & Ilovaisky 1995; see also Shrader et al. 1997; Castro-Tirado, Ortiz & Callego 1997). The only other SXT seen to exhibit ‘mini-outbursts’ is GRS 1009−45 (X-ray Nova Vel
**Fig. 8.**

- **a.** V band light curve of GRO J0422+32. Data are from Castro-Tirado et al. 1993, Mineshige 1994, Bartolini et al. 1994, Callanan et al. 1995, Chevalier & Ilovaisky 1995, Kato, Mineshige & Hirata 1995, King, Harrison & McNamara 1996, Goranskii et al. 1996, and measurements reported in IAU Circulars, see Chevalier & Ilovaisky 1995. Visual and V band (b.), and B band (c.) light curves of A 0620−00. Arrows in b. and c. denote lower limits on the magnitude from visual and photographic B measurements, respectively.

1993, MM Vel; Bailyn & Orosz 1995; see Fig. 9). In Fig. 8 we show the V band optical light curve of GRO J0422+32 and the V and B band light curves of A 0620−00 on the same time scale. The main outbursts of A 0620−00 and GRO J0422+32 have a very similar duration. It is therefore interesting to investigate any possible ‘mini-outbursts’ in A 0620−00, which might have been unnoticed.

There are several visual reports by Duruy (1976) around 470 and 530 days after the start of the outburst and an estimate by Cragg ~505 days after the start of the outburst (see Bateson 1976), which indicate that A 0620−00 was seen ~4–5 magnitudes above its quiescent level of ~18 mag. However,
measurements done by Oke (1977) 472 and 474 days after the start of the outburst showed the system to be in quiescence, almost simultaneous with some of Duruy’s estimates. This, therefore, casts some doubt on the visual estimates, and the existence of any possible rebrightening\(^4\).

### 4.3 A comparison with other short period SXTs

In Fig. 9 we show the compilation of optical and X-ray observations of the short period SXTs GRO J0422+32, GRS 1009−45, A 0620−00, GS 2000+25 (X-ray Nova Vul 1988, QZ Vul) and GS 1124−68 (X-ray Nova Mus 1991, GU Mus)\(^5\), where the orbital period increases from GRO J0422+32 (∼5.1 hr) to GS 1124−68 (∼10.4 hr), see e.g. Shahbaz & Kuulkers (1998). This figure shows that apart from secondary and tertiary maxima, which have been previously reported in X-ray and optical (e.g. Chen et al. 1997, and references therein), all the outbursts appear to last for ∼250 days. Also, for A 0620−00, GS 2000+25 and GS 1124−68 both the optical and X-ray show drops in the flux away from the expected exponential decay around ∼150 days after the start of the X-ray outburst, followed by the tertiary maximum. In the optical there is a drop in magnitude in GRS 1009−45 ∼150 days after the start of its outburst, which has previously been related to one of its mini-outbursts (Bailyn & Orosz 1995). A sudden fading of the optical flux of GRO J0422+32 has been reported by Bartolini et al. (1994), which occurred ∼148 days after the outburst (not plotted in Fig. 9). Optical data taken shortly thereafter (Kato et al. 1995) indicate that this drop lasted at least ∼0.42 days. This all suggests that the morphology of the outbursts in the optical and X-rays of these SXTs is very similar. Similar behaviour may be seen in the 1971 outburst light curve of 4U 1543−47 as recorded by \textit{UHURU, OSO-7} and \textit{Vela} (Li, Sprott & Clark 1976; see also Chen et al. 1997): ∼140 days after the maximum outburst (which showed an exponential decay together with a secondary maximum) the X-ray intensity starts to show various deep drops below the extrapolated exponential decay.

For GRS 1009−45 and GRO J0422+32 no soft X-ray information (typically

\(^4\) Duruy used an AAVSO preliminary chart during outburst, whereas after the final decline of the system, he used a personal sequence. Like all the visual observers, even the most experienced, Duruy may well have made a mistake, but he never corrected these observations after their publication in the AFOEV bulletin (Schweitzer 1997, private communication). We note that Duruy later also reported several upper limits, which means he at least observed a variable star.

\(^5\) We note that West (1991) erroneously reports on an observation obtained on Jan. 13.25 UT 1988 (JD 2447269.75) by G. Pizarro, where the counterpart was found at 17–18 mag; this magnitude estimate is in fact obtained from an ESO Schmidt plate on Jan. 29 1976 taken by G. Pizarro (see Della Valle, Jarvis & West 1991a; 1991b).
Optical (○) outburst light curves of GRO J0422+32 (V), GRS 1009–45 (V), A 0620–00 (V), GS 2000+25 (R), and GS 1124–68 (V) and the corresponding X-ray light curves as a function of the start of the X-ray outburst. For references to the optical data of GRO J0422+32, see Fig. 8. The optical V band data of GRS 1009–45 are from Bailyn & Orosz (1995), Masetti, Bianchini & Della Valle (1997) and Della Valle et al. (1997), while those of GS 1124–68 are from Bailyn (1992), King, Harrison & McNamara (1996), and Della Valle, Masetti & Bianchini (1998). The R band data of GS 2000+25 are from Borisov et al. (1989) [see also Karitskaya (1989)] and Charles et al. (1991). We have added a constant of 0.8 to the data of Borisov et al. (1989) so that they agree with those of Charles et al. (1991). We have also included the V band data (near 210 days after start of the outburst of Chevalier & Ilovaisky (1990) and applied a colour correction of ~1 (see Charles et al. 1991). The X-ray data are taken from Chen et al. (1997). T = 0 corresponds to 2448838.5, 2449241.6, 2442627.5, 2447273.8 and 2448265.3 for GRO J0422+32, GRS 1009–45, A 0620–00, GS 2000+25, and GS 1124–68, respectively.

2–20 keV) is available, so it is difficult to compare them with the X-ray light curves of the other SXTs, although we note that the hard X-ray light curves of A 0620–00 (this paper) and GS 1124–68 (Ebisawa et al. 1994) become more irregular and less compatible with a so-called ‘fast-rise exponential decay’ (FRED) light curve, which seems to be similar to GRS 1009–45. However, this does not apply to GRO J0422+32 (Fig. 9).
4.4 The outbursts of A 0620–00 and AL Com

It was quickly recognized that the optical amplitude of the outburst of A 0620–00 was comparable to that of dwarf novae such as VY Aqr, UZ Boo, AL Com and WZ Sge (e.g. Eachus et al. 1976; Kholopov & Efremov 1976; Richter 1986). Also the recurrence times of the outbursts of these systems were found to be similar to e.g. A 0620–00 and Aql X-1 (V1333 Aql), see e.g. Richter (1986). In fact, all short period SXTs have large optical amplitude outbursts (see e.g. Tanaka & Lewin 1995; Shahbaz & Kuulkers 1998; see also Fig. 9). The dwarf novae mentioned above all belong to a subclass of the SU UMa stars, called ‘Tremendous Outburst Amplitude Dwarf novae’ (TOADs, Howell, Szkody & Cannizzo 1995), also referred to as WZ Sge stars (e.g. Warner 1995; see a discussion in Patterson et al. 1996).

The last outburst of AL Com, in 1995, has been fairly well covered by various observers (Howell et al. 1996; Patterson et al. 1996; Nogami et al. 1997). In Fig. 10 we have superposed the outburst light curve of AL Com on that of A 0620–00. Note that the x-axes of AL Com and A 0620–00 scale by a factor ∼5.3, while the y-axis scales are the same (but have been shifted in magnitude). This shows that the outburst amplitudes are similar and that the shape of the outburst of AL Com is almost a carbon copy of that of A 0620–00, including the two enhancements during the exponential decline, the drops in intensity at the end of this decline, the final bump at the end of the outburst and the small local maximum before the final fast decay to ∼1 magnitude above their quiescence values.

5 Discussion

In this paper we have compared the outburst light curves at various wavelengths of A 0620–00. Although we confirm several of the features reported earlier, we found various new features not seen before.

5.1 X-ray delay

During several stages of the outburst we found evidence for delays between the optical and X-ray. The peak of the secondary maximum was reached ∼5 days earlier in the optical. The infra-red activity associated with the secondary maximum started even a few days earlier with respect to the optical and X-ray. During the trough of the outburst, drops in intensity are consistent with a similar delay of ∼5 days. Near the end of the outburst a ‘hiccup’ occurred.
in the optical, which was followed \(\sim 5\) days later in the X-rays. The broad tertiary maximum started about two weeks earlier in the optical with respect to X-rays; also the peak of this broad maximum was consistent with a similar delay.

A delay between the optical and X-ray was also reported for GS 1124—68 by Ebisawa et al. (1994). They found that the peak of the X-ray outburst was reached \(\sim 4\) days later than the peak of the optical outburst, i.e. a very similar timescale to A 0620—00. We note that we cannot say with certainty if a similar delay is present at the peak of the outburst of A 0620—00. More recently, a delay of \(\sim 6\) days between the optical and X-ray was found at the start of the outburst of the superluminal SXT GRO J1655—40 (Orosz et al. 1997).

The delays seen between the optical and X-rays indicates that most of the processes associated with the outburst occur in the outer parts of the accretion
disk. The outburst starts somewhere in the outer disk, because of the presence of an inner advection-dominated accretion flow (ADAF) which prevents forming an inner disk region during quiescence (see Narayan, McClintock & Yi 1996; Lasota, Narayan & Yi 1996; Narayan, Barret & McClintock 1997; Hameury et al. 1997). Additional X-rays appear only when the disk is able to extend inwards and therefore causes a delay. Renewed activity in the outer parts of the disk (e.g. Ichikawa & Osaki 1994; King & Ritter 1998) may explain the delays seen between the optical (and infra-red) and X-rays (not all material has been accreted and it may already have returned to its cool state, or fresh material has been provided by the companion star). Such renewed activity might be induced by the intense irradiation causing the outer parts of the accretion disk to return to a high state again (e.g. King & Ritter 1998). We note that activity in the outer disk is also revealed by the onset of superhumps in the SXTs, which always occur just after the secondary maximum (see O’Donoghue & Charles 1996). The fact that we see optical superhumps despite the luminous accretion disk has also been attributed to irradiation (O’Donoghue & Charles 1996, see also Billington et al. 1996).

5.2 Outburst decay and local X-ray maxima

As already noted, the first exponential decay phase of the outburst of A 0620−00 is slower than its second exponential decay phase. This means that in the case of A 0620−00 the secondary maximum is a temporary enhancement on the first exponential X-ray decay light curve. Also in the optical the secondary (and ‘intermediate’) maxima decay more rapidly in order to resume the same exponential decay as seen before the secondary maximum. In the optical this occurs much earlier than in X-rays (~1 week in the optical versus ~2 months in X-rays). For the other (short-period) SXTs with comparable outburst light curves this seems not to be the case, i.e. the decay timescales before and after the secondary maxima are similar (see e.g. Augusteijn et al. 1993; Chen et al. 1993; 1997; see also Fig. 9).

It is also evident from the overall outburst light curve of A 0620−00 that the time difference between the main maximum and the secondary maximum and that of the secondary maximum and tertiary maximum are not of the same order, as seems to be the case for GS 2000+25 (Augusteijn et al. 1993, see also Chen et al. 1993). However, the inferred third maximum by Augusteijn et al. (1993) is not the real tertiary maximum; the tertiary maximum is probably reached ~200 days after the peak of the outburst (see Kitamoto et al. 1992; Terada et al. 1998; see also Tanaka & Shibazaki 1996). Also for GS 1124−68 the time differences between the different maxima are not similar (see Ebisawa et al. 1994; see also Fig. 9), and its tertiary maximum is ~200 days after peak of the outburst (see Ebisawa et al. 1994; see also Tanaka & Shibazaki 1996),
i.e. similar to A 0620−00 and GS 2000+25. It has recently been shown that the time of the secondary maximum in SXTs is related to the viscous time scale of an irradiated disk (Shahbaz et al. 1998b; see also King & Ritter 1998). The time of the tertiary maximum seems to be unrelated to this.

It is interesting to note, however, that the times of the expected tertiary maxima of the outbursts of A 0620−00, GS 2000+25 and GS 1124−68 in the model of Augusteijn et al. (1993) are consistent with the times of start of the spectral hardening (see also next Section; A 0620−00: this paper; GS 2000+25: Kitamoto et al. 1992; Terada et al. 1998); GS 1124−68: Kitamoto et al. 1992; Ebisawa et al. 1994). Moreover, the timescale between the primary and secondary maximum of the GRO BATSE hard X-ray outburst light curve of GRO J0422+32 as derived by the model of Augusteijn et al. (1993) is similar to the time of appearance of the first ‘minioutburst’ with respect to the end of the X-ray outburst and the time between the two ‘minioutbursts’ (see Callanan et al. 1995, Chevalier & Ilovaisky 1995).

5.3 X-ray spectral hardening

For the first time we have demonstrated that A 0620−00 exhibited considerable hardening ∼100 days after the start of the outburst. A similar hardening at nearly the same time after outburst maximum has also been seen in GS 1124−68 and GS 2000+25 (Kitamoto et al. 1992; Ebisawa et al. 1994; Terada et al. 1998). The X-ray spectral and power spectral behaviour in GS 1124−68 and GS 2000+25 just before the hardening is consistent with canonical black-hole high-state behaviour (and maybe also for A 0620−00, see Section 2), whereas after the hardening it is consistent with the canonical black-hole low-state behaviour (Ebisawa et al. 1994; Miyamoto et al. 1994; Terada et al. 1998). We therefore suggest that the power-spectral behaviour after the start of the spectral hardening in A 0620−00 might have shown low-state like behaviour as well.

The time of maximum X-ray spectral hardening is close to when the ∼7.8-day modulations in the X-ray light curve of A 0620−00 are strongest. Similarly, the time of maximum X-ray spectral hardening in GS 1124−68 and GS 2000+25 also occur simultaneously with the drops in intensity, i.e. ∼150 days after the start of the outburst. This suggests a connection between the X-ray spectral hardening and the occurrence of periodic modulations or drops in intensity (see also Section 5.4).

Recently, a self-consistent model of accretion flows around black holes with various M has been put forward by Esin, McClintock & Narayan (1997; see also Esin et al. 1998). Their accretion flow consists of an ADAF and an outer
(thin) accretion disk. In addition above the orbital plane there is a hot corona. $\dot{M}$ determines the size of the ADAF region and the density of the corona. In this way they could explain the different states seen in black-hole binaries, the off-state, low state, high state and (possibly) the very-high state. The spectral hardening $\sim 150$ days after the outburst is identified with the transition from the high state to low state, i.e. the intermediate state in their model.

We note that such hardening is probably not confined to black-hole SXTs. It has recently been suggested that the hardening near the end of the outburst of the neutron star SXT Aql X-1 (Zhang, Yu & Zhang 1998) after a small secondary maximum is a similar phenomenon (Shahbaz et al. 1998a). If this is true, this should manifest itself in a change in the power spectral shapes, possibly resembling black-hole low-state behaviour during the hardening.

5.4 Dips and intermediate maxima

During the outburst the X-ray light curves show that various drops in intensity occurred, lasting from about one day to several days. They occurred $\sim 87$, $\sim 103$, and $\sim 228$ days after the start of the outburst. Possibly, also the precursor may in fact represent a dip. In addition to these dips, periodic drops in intensity have been seen in X-ray and optical with a period of about 7.8 days (see Section 2), and possibly also in the infra-red (this paper). The occurrence of the dips are consistent with the $\sim 7.8$ day modulation period.

It has been suggested that the $\sim 7.8$-day modulation is the beat period between the orbital period and the (possible) superhump period (Zhang & Chen 1992), i.e. the disk precession period (see e.g. Priedhorsky & Holt 1987). In the SXTs where superhumps have been seen the period excess was found to be between $\sim 1–2\%$ (O’Donoghue & Charles 1996). This has also been found for the TOADs (see Kuulkers, Howell & van Paradijs 1996, and references therein), and has been related to the extreme mass ratio in these systems. If this also holds for A0620–00, the estimated superhump period would be 7.83–7.90 hrs, which leads to a beat period between 17–32 days. This is consistent with estimates of the beat period period from its relation with the orbital period and the mass ratio (see e.g. Warner 1995), i.e. $\sim 18–19$ days. Hence the $\sim 7.8$-day modulation cannot be related to the beat period between the orbital period and the (possible) superhump period.

Alternative models include e.g. intrinsic oscillations of the companion star, modulating the accreted matter onto the black hole (Ciatti et al. 1977). We note that near the time of the strong $\sim 7.8$-day modulations the X-ray spectra harden (see previous Section), which suggest a connection between the two. It might be that the transition radius between the outer thin disk and inner
ADAF flow in the model of Esin et al. (1997) is oscillating around that time, i.e. the transition radius moves inwards and outwards on a time scale of $\sim 8$ days, which therefore modulates the accretion rate and subsequently the amount of X-rays. Another speculation might be that the heating/cooling waves oscillate inwards and outwards between certain radii, as a result of a modulation in the strength of X-ray irradiation. It remains to be seen if such mechanisms do indeed exist. Moreover, the delay in optical and X-rays should also be explained in such models.

The dip in X-rays $\sim 87$ days after the start of the outburst has not been noted before. As we have shown this corresponds to a short rise in intensity or flare at hard energies ($\gtrsim 6$ keV), which indicates the X-ray spectrum suddenly pivots for a short time. In the optical we see that there may be a depression in the light curve, but shortly afterward the brightness increased above the expected exponential decline, which resulted in another local maximum, a so-called ‘intermediate’ maximum, $\sim 30$ days after the secondary maximum. A similar ‘intermediate’ maximum may be present in the infra-red, whereas there is no indication for such a maximum in X-rays.

The $\sim 30$ days interval between the secondary maximum and ‘intermediate’ maximum is comparable to the viscous time scale in an irradiated accretion disk with parameters appropriate for A 0620 $-00$ (King & Ritter 1998; see also Shahbaz et al. 1998b). If irradiation triggers a thermal instability in the outer accretion disk, new material will accrete one viscous time scale later. This has been put forward as the explanation for the secondary maximum as an echo of the primary maximum by King & Ritter (1998; we refer to e.g. Cannizzo 1998 and references therein for other models on the cause of the secondary maximum). We suggest that the secondary maximum induces again enhanced irradiation which may then show up one viscous time scale later. It is not clear to us, however, why this would cause the X-ray spectrum to pivot around that time, and why it does not show up as an ‘intermediate’ maximum in the X-ray light curve.

The only other SXT where another local maximum has been reported which did not coincide with a local maximum in X-rays is GRO J0422+32. Shrader et al. (1994) reported a secondary maximum in the ultra-violet, which occurred $\sim 38$ days after the maximum of the GRO BATSE outburst. However, the GRO BATSE light curve is that for high ($\gtrsim 20$ keV) energies. For GS 1124 $-68$ the soft X-ray ($\sim 1$–$10$ keV) light curves differs from that in hard X-rays ($\sim 10$–$40$ keV light curves (see Ebisawa et al. 1994), and this could also apply to GRO J0422+32. The local ultra-violet maximum might therefore have been simultaneous with a local soft X-ray maximum, which is expected to exist $\sim 35$ days after outburst maximum (Shahbaz et al. 1998b).

Although the time of the ‘hiccup’ at the end of the outburst is consistent with
the minima expected in the $\sim 7.8$ days modulation, interestingly the time difference between the optical maximum of the tertiary peak and the ‘hiccup’ is also on the order of 30 days. This may suggest a similar cause for the ‘hiccup’ as that proposed for the ‘intermediate’ maximum, where now the ‘hiccup’ is a response to the tertiary maximum. We note that a similar ‘hiccup’ might have been seen at the end of the outburst of GS 2000+25 (Chevalier & Ilovaisky 1990).

5.4.1 TOADs and SXTs

We have shown here that the outburst light curve of the SXT A 0620−00 is very similar in shape to that of the TOAD AL Com. Also the structure of the 1978 outburst light curve of WZ Sge (Patterson et al. 1981) is very similar to that of AL Com (see Howell et al. 1996) and A 0620−00, having a similar exponential decay, drops in magnitude near the end of the outburst and a ‘bump’ at the end of the outburst. The timescales in the outbursts of A 0620−00 and AL Com differ by a factor of $\sim 5.3$. This is close to the ratio of the orbital periods of A 0620−00 and AL Com ($\sim 84$ min, see Howell et al. 1996), i.e. $\sim 5.5$. We note that the mass ratio of AL Com is close to A 0620−00, i.e. $q \lesssim 0.15$, with likely values between 0.033–0.075 (Howell, Hauschildt & Dhillon 1998). This shows that the optical outburst light curve is not governed by the mass of the compact object, but related to the (similar) disk properties.

Interestingly, the morphology of the orbital light curve of AL Com in quiescence is rather unstable (Abbott et al. 1992; Howell et al. 1996, and references therein), which has also been reported for A 0620−00 by Haswell (1996) and Leibowitz, Hemar & Orio (1998). We note that the optical spectra of A 0620−00 in quiescence have also been reported to change with time (Murdin et al. 1980; Orosz et al. 1994).

Masetti & Regős (1997) suggested that SXTs share properties with another SU UMa subclass, i.e. the so-called ER UMa stars. This was based solely on the comparison of the shape and appearance of (super) humps in the light curves of SXTs and ER UMa stars. ER UMa stars are at the other extreme of the SU UMa class, i.e. during quiescence they have highest mass transfer rates compared to other SU UMa stars in quiescence. They therefore show very frequent outbursts with short quiescent periods, 40–50 days, while their outbursts are of relatively small amplitude, $\Delta V \sim 3$ (Kato & Kunjaya (1995). These are properties clearly not shared by the SXTs.

The outburst and quiescence properties of SXTs have been shown, however, to be very similar to those of TOADs, having a fast rise, large outburst amplitude, a slow outburst decay, drops in intensity near the end of the main outburst, and/or post-outburst brightenings (Kuulkers et al. 1996). Our comparison
between A 0620−00 and AL Com gives additional support for their similarity. The similarities between the TOADs and SXTs reflect that both have low mass ratios and very low mass transfer rates, $\dot{M}$ (Kuulkers et al. 1996).

It is clear that these light curves represent some very generic behaviour. This may be due to a pure viscous evolution, i.e. the outburst disk just evolves under a hot-state viscosity, without the intervention of cooling fronts, until possibly the end of the outburst. Hence any mechanism that prevents the cooling front travelling in from the outer edge of the disk for a sufficiently long time will produce these light curves. In the SXTs irradiation naturally provides that mechanism (e.g. Chen et al. 1993; Van Paradijs 1996; King 1998; King & Ritter 1998), whose presence is suggested (at least near maximum of the outburst) by observations (see e.g. van Paradijs & McClintock 1994; 1995; Shahbaz & Kuulkers 1998)\(^6\). For the outburst of AL Com irradiation may prevent the cooling front from propagating as well, but it is more complicated in this case (see King 1997). If confirmed by more detailed modelling, it may be possible to provide a unified explanation of both cases.

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\(^6\) The amount of optical radiation reprocessed from X-ray irradiation is still a subject of debate (see e.g. Lasota & Hameury 1998). Current versions of the disk-instability model suggest that only $\sim$1 mag of the optical light during the first months of the outburst is due to X-ray irradiation (see Cannizzo 1998).
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