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Research Paper

Outbursts of the black hole X-ray transient KV UMa (XTE J1118+480) in the optical band

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Abstract

KV UMa (XTE J1118+480) is an X-ray binary that is known to undergo outbursts in 2000 and 2005. This paper presents the discovery of a large outburst starting in 1927 on the archival photographic plates and an analysis of the long-term optical activity of this system. We used the photographic data from DASCH (Digital Access to a Sky Century @ Harvard). We placed the 1927 outburst in the context of the observed outbursts of KV UMa. We show that it is a double event, with a precursor similar to the one of the outbursts in 2000. We find a big difference between the 1927 and 2000 outbursts as regards the length of the gap between the precursor and the main outburst. It is more than 250 d in 1927, whereas it is about 20 d in 2000, although the brightnesses of all peaks are mutually comparable. We also show that the individual optical outbursts of KV UMa differ from each other by the duration of the stage of a slow decline of brightness (sometimes roughly a plateau). This determines the length of the entire main outburst. Both the peak magnitude and the brightness of the outburst when the slow decline transitions to a steep final decaying branch plausibly reproduce in all three outbursts. In the interpretation, the short duration of the precursor is caused by the fact that only the thermal-viscous instability operated in the accretion disk while also the tidal instability of the disk contributed in the subsequent main outburst.

Keywords: Accretion, accretion disks – Methods: observational – Radiation mechanisms: general – Stars: individual: KV UMa, XTE J1118+480 – X-rays: binaries

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1. Introduction

The accretion disk of low-mass X-ray binaries (LMXBs) suffers from a thermal-viscous instability if the time-averaged mass transfer rate from the donor to the compact accretor lies between certain limits. This causes occasional outbursts in LMXBs. Such systems are called the soft X-ray transients (SXTs) [e.g. Lewin et al. (1995); Dubus et al. (2001)]. A typical recurrence time (cycle-length) of these outbursts and its time variations can be determined from a long (e.g. decades) series of observations. The typical duration of the outbursts of SXTs is on the order of several weeks to several months.

The X-ray outburst of XTE J1118+480 (KV UMa) was discovered in 2000 by Remillard et al. (2000). Uemura et al. (2000, 2002) found that it was a double event, with a separation clearly present both in the X-ray and in the optical bands. A long main outburst had a short precursor, with the peak X-ray and optical fluxes comparable to those of the subsequent main outburst. The optical maximum and the onset of the outburst preceded those in the X-ray region during the main outburst. This indicates an 'outside-in' type outburst. The small ratio of the X-ray and the optical luminosities suggests that the optical flux of the disk was dominated by viscous heating, not by the X-ray irradiation. They also detected superhumps throughout this outburst. Superhumps are powered by spiral shocks in the fluid disk (Smith et al. 2007). Their occurrence is a more general feature of activity of KV UMa because they were present also in the next outburst in 2005 (Zurita et al. 2006).

Zurita et al. (2006) discovered another outburst of KV UMa in 2005. A search in the *RXTE*/ASM data did not find any precursor, in variance with the 2000 outburst. The X-ray spectrum of the 2005 outburst was hard, the light curve and the ratio of the optical to X-ray luminosity resemble the minioutbursts in GRO J0422+32 and XTE J1859+226. Zurita et al. (2006) argue that the infrared emission of XTE J1118+480 was dominated by a jet, whereas the optical one was produced by the disk during the peak of the 2005 outburst.

According to Markoff et al. (2001), KV UMa displayed a significant jet contribution in the radio–IR band and in X-rays during its 2000 outburst. Hynes et al. (2006) showed that the jet contribution to the optical and near infrared was similar in the 2000 and 2005 outbursts. Brocksopp et al. (2010) found the differences in the morphology of the light curves of the 2000 and 2005 outbursts in various bands, from X-ray to radio. They attributed them to the contributions of emission from multiple components, in particular to the jet and the accretion disk.

The observations of KV UMa in quiescence show that it contains a black hole (BH) with the mass of 6.9–8.2 $M_\odot$ and the secondary with the spectral type K5V–M1V. The orbital period $P_{\rm orb}$ is 0.17013 d (4.083 h). The estimated distance is 1.8 ± 0.6 kpc (McClintock et al. 2001; Khargharia et al. 2013).

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This paper reports a study of the long-term activity of KV UMa in the optical band and the discovery of another double outburst. We show how its properties can be placed in the activity of this X-ray binary.

2. Observations

The digitized photographic data of KV UMa were obtained from DASCH (Digital Access to a Sky Century @ Harvard http://dasch.rc.fas.harvard.edu/lightcurve.php; (Grindlay et al. 2012; Grindlay & Griffin 2012). This database provides SExtractor-based photometry of every resolved object. The data used for this analysis cover blue spectral region.

The exposure time of the plates varied and was of the order of tens of minutes (between about 30 minutes and an hour, sometimes longer than an hour). This band is similar to the *B*-band, so we will be referring to the brightness measured on these plates as mag (*B*). The coverage of the light curve of KV UMa spans between the years 1887 and 1989. One plate of the field of KV UMa was usually obtained per night.

3. Data analysis

The DASCH database enables to display the field (square) around the object (KV UMa in our case) with the field size of 20 arcmin. Its inspection enables us to assess whether the outburst of KV UMa, detected on the digitized plates, is influenced by artefacts. All digitized plates on which KV UMa was influenced by the plate defects were thus rejected. This led to the detection of a big outburst and its time evolution, used for further analysis. About 1 500 additional plates free of artefacts were used for determining the upper limits of brightness of KV UMa. They enable us to constrain the brightness variations of this object. The resulting long-term light curve of KV UMa, determined from the DASCH data, is displayed in Figure 1(a). The DASCH database does not contain the observations of KV UMa for a segment of several years, centred on JD 2 437 000. This gap was noticed, for example, by Lund et al. (2016). It represents a time segment between JD 2 434 448 and JD 2 439 946 for KV UMa.

To show the long-term activity of KV UMa after the end of the DASCH observations, Figure 1(a) contains also charge-coupled device (CCD) observations of the outbursts in 2000 (Uemura et al. 2002) and 2005 (Zurita et al. 2006). Only the detections are shown. The quiescence of KV UMa is out of the range of this diagram.

We discovered a large outburst with several peaks, starting in 1927. The light curve of this outburst is defined by 11 detections on the plates. This outburst was a double event, with each of its two peaks confirmed by the detections on several plates (Figure 1(b)). These peaks were separated by a dip of at least 2 mag. The standard deviations of brightness of each data point (from the original data file) enable us to assess the reality of the features in the light curve. A steep rise of brightness of the main outburst, followed by a gradual decrease, can be securely identified in DASCH data.

As regards the significance of the first peak (precursor), for example, the brightness of KV UMa in JD 2 424 996.7 was 12.97 ± 0.14 mag, the limiting magnitude of the plate was 13.94. The separation of the brightness of KV UMa from the background was 0.96 mag, which suggests the significance of about 6.9σ. The significance of the second, broad peak (the main outburst) was even higher than 12σ on some plates. The upper limits of brightness of KV UMa on the plates [JD 2 424 969.7 (limit. mag 13.67) and JD 2 425 029.6 (limit. mag 13.33)] constrain the duration of the precursor to be at most about 60 d. As for the main outburst, the upper limits of brightness of KV UMa on the plates [JD 2 425 240.9 (limit. mag 14.29) and JD 2 425 374.6 (limit. mag 14.34)] constrain its duration to be about 134 d.

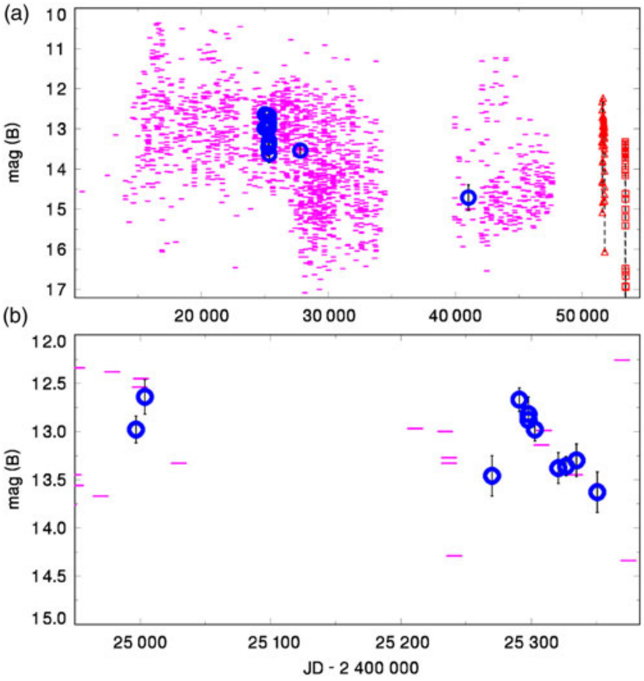

Figure 1. **(a)** Long-term light curve of KV UMa. The open circles represent the detections in the DASCH database. The standard deviations of brightness, listed in the original data file, are displayed for each data point. The short horizontal lines mark the upper limits of brightness on the plates which did not detect KV UMa. Triangles mark the CCD observations of the 2000 outburst (Uemura et al. 2002). Squares represent the CCD observations of the 2005 outburst (Zurita et al. 2006). **(b)** Detail of the 1927 main outburst with its precursor. See Section 3 for details.

To show that the observations of KV UMa were not influenced by artefacts and the 1927 outburst was real, Figure 2 displays the field of KV UMa on the DASCH plates in the important stages of this event. It was prepared by SAOImage DS9[a]. The position of KV UMa is coincident with the centre of each panel. The brightness of KV UMa and the prominence of this object with respect to the background can be compared with that of the check star, marked as C [$11^{\mathrm{h}}18^{\mathrm{m}}46.3^{\mathrm{s}}$; $+47°54'44''$ (equinoctium 2000)] in Figure 2.

Figure 2(a) displays KV UMa in the time of the precursor (JD 2 424 996.68, plate ay01440). This object, slightly fainter than the check star C, stands out clearly from the background. On the contrary, KV UMa is below the detection limit between the two peaks (outbursts) in Figure 2(b) (JD 2 425 240.87, plate ay01963) although the star C is clearly detectable. Figure 2(c) shows KV UMa in its main outburst (JD 2 425 297.75, plate rh00065), with its brightness almost comparable to that of the star C. This confirms that the 1927 outburst was a double event. The result of the inspection of the images is that KV UMa can be identified on several pixels of a digitized plate, and its shape is consistent with those of the normal stars. We conclude that this outburst is a real phenomenon.

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[a] http://ds9.si.edu/site/Home.html

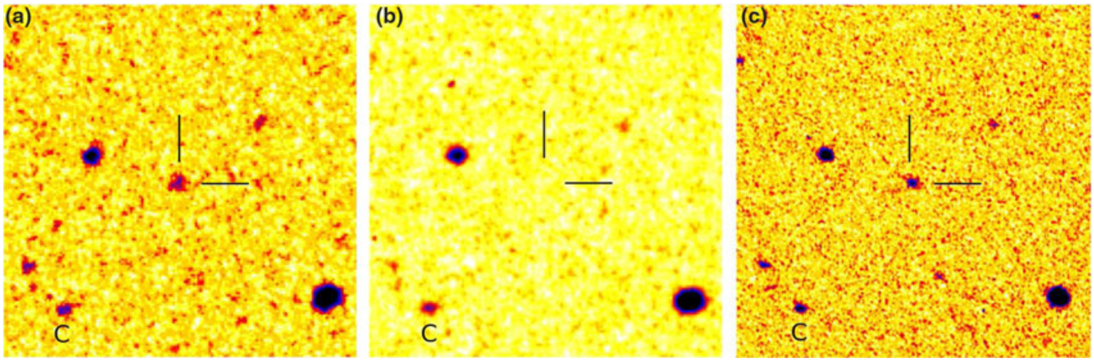

Figure 2. Field of KV UMa on the DASCH digitized photographic plates during the precursor of the main outburst (JD 2 424 996.68) **(a)**, in the time between the two outbursts (KV UMa is below the detection limit) (JD 2 425 240.87) **(b)**, and during the main outburst (JD 2 425 297.75) **(c)**. The position of KV UMa is located in the centre of each panel and is marked by the lines. The check star is abbreviated as C. North is up, East to the left. The field size is 20 arcmin. See Section 3 for details.

To place the 1927 outburst in the context of the observed outbursts of KV UMa, we attempted to superpose their light curves. We used the curves of Uemura et al. (2002) for the 2000 outburst and the observations of Zurita et al. (2006) for the subsequent 2005 outburst. It is true that the bands, in which the densely populated light curves of each of these outbursts were obtained, differ (the band of the DASCH plates is close to the B-band, the data of Uemura et al. (2002) are in the V-band, the measurements of Zurita et al. (2006) are in the R-band). Nevertheless, since the peak-to-peak amplitude of these outbursts is very large (about 5 mag) and the colour index $B - R$ is only 0.3–0.4 mag according to the light curves of Zurita et al. (2006), this does not influence the result significantly.

A folding of the light curves considers the most dominant outbursts (if they were the multiple events), not the precursors (1927 and 2000) or the minioutbursts observed in the late decay of the 2005 outburst. The peak of the minioutburst in 2005 was at about 16.5 mag (Zurita et al. 2006), below the detection limit of most DASCH data.

As shown in Figure 3, the 2000 main outburst served as a template for folding the decaying branches of these events; the long plateau (abbreviated as stage P) was followed by a final steep decline (stage F). A good fit was obtained for a match of the 2005 outburst to the template, as regards stage F and stage P. The detections of KV UMa in the DASCH data since the peak of the 1927 main outburst can be associated with a slow decay (similar to stage P of the 2000 outburst). A possible undulation of the decay, suggested by some data points, is within the observational uncertainties. The final detection of the 1927 outburst shows a further decay of brightness. A match to the template shows that this can be associated with stage F.

The separation between the precursor and the start of the main outburst is roughly three times larger in the 1927 outburst than in the 2000 one, although the peak magnitudes of these events in Figure 3 can be considered mutually similar.

We noticed that the DASCH database contains also two other detections abbreviated here as O1 and O2 (each of them was on a single plate) (Figure 1(a)). Since the quiescent brightness of KV UMa of about 19 mag(R) (Zurita et al. 2006) is considerably fainter than the upper limits in the DASCH data, it is below their detection limit. O1 and O2 therefore indicate brightenings. The brightness of O1 in JD 2 427 783.9 was 13.54 ± 0.14 mag, the limiting magnitude of the plate was 14.51. The separation of the brightness of KV UMa from the background was 0.97 mag, which suggests the significance of this outburst to be 6.9σ. The upper limits of brightness of KV UMa on the neighbouring plates [JD 2 427 778.9 (limit. mag 15.37) and JD 2 427 785.9 (limit. mag 15.24)] constrain the duration of this outburst to 7 d or less. The brightness of O2 in JD 2 441 035.6 was 14.71 ± 0.32 mag, the limiting magnitude of the plate was 15.25. This suggests a low significance of this outburst ($< 2\sigma$).

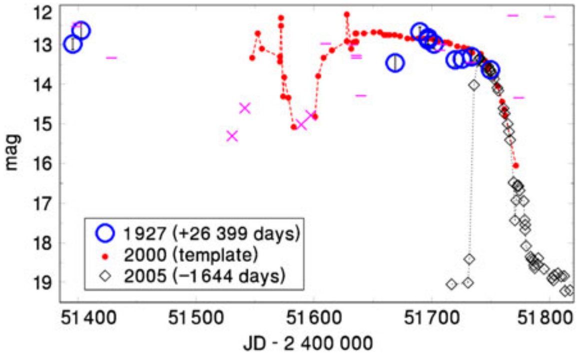

Figure 3. Light curves of three folded outbursts of KV UMa. The 2000 main outburst serves as a template for folding the decaying branches. The upper limits of brightness of the 2000 outburst are represented by x. The short horizontal lines mark such limits in the 1927 outburst. See Section 3 for details.

4. Discussion

This paper brings new results regarding the long-term activity of the BH transient KV UMa in the optical band. We discovered a large outburst (1927) on the archival photographic plates. They enable us to study the long-term activity of this source. We also place this outburst in the context of the observed outbursts of KV UMa.

In the interpretation, we consider both peaks which occurred in 1927/1928 as the precursor and the main outburst. Although the time between the precursor and the start of the main outburst is about 3.25 times longer than the length of the main outburst, this separation is much shorter than the time to other observed neighbouring outbursts. Another such a double event was observed in

2000 (Uemura et al. 2000, 2002). Although the brightnesses of all of these peaks are mutually similar, we find a big difference between the 1927 and 2000 events as regards the gap between the precursor and the start of the main outburst. The gap is about 260 d between the precursor and the start of the main outburst in 1927, whereas it is only about 20 d in 2000, although the 2000 main outburst was considerably longer than the 1927 one.

Since no precursor was detected for the 2005 outburst (Zurita et al. 2006), we treat it in the same way as the main 1927 and the 2000 outbursts because of the properties of its light curve discussed below. We show that the individual optical main outbursts of KV UMa differ from each other mainly by the duration of stage P defined in Section 3. This stage also determines the length of the entire main outburst [the 2005 outburst only briefly touched it but because it displayed superhumps (Zurita et al. 2006), it belongs to the superoutbursts like the 2000 main outburst (Uemura et al. 2002)].

The decay rate and brightness evolution of the 1927 outburst in stage P are in rough agreement with that of the 2000 main outburst. Following Uemura et al. (2002), this indicates that the optical flux was dominated by the viscous heating of the ionized accretion disk, not by the X-ray irradiation, in both of these outbursts. The viscous heating of the disk in KV UMa is dominant no matter how long stage P is, and also the light curve in the peak of the 2005 outburst is consistent with such a heating [confirmed also by the small X-ray to optical flux ratio (Zurita et al. 2006)]. In this framework, we interpret stage P of all three outbursts as the viscous plateau in which the disk is ionized out to its outer rim, similarly as in some dwarf novae (Smak 1984; Warner 1995; Hameury et al. 1998).

The profile of the light curve and the brightness in the surroundings of the transition from stage P to stage F turn out to be reproducible for all three outbursts of KV UMa. Using a thermal-viscous instability of the accretion disk (Smak 1984; Hameury et al. 1998), this transition starts when the outer disk region begins to recombine because the mass accretion caused a decrease of its column density; cooling front thus begins to propagate across the disk.

KV UMa was subject to the thermal-tidal instability (TTI) (Osaki 1989; Osaki & Kato 2013) of the accretion disk during its 2000 and 2005 outbursts because of the detected superhumps (Uemura et al. 2002; Zurita et al. 2006). They are therefore analogous to the superoutbursts of the SU UMa dwarf novae. Because of the shapes of the light curves and brightnesses of the outbursts in Figure 3, we interpret also the 1927 event as a superoutburst. Since the X-ray luminosity of the 2000 outburst was about 1.2×10^{36} erg s^{-1} (McClintock et al. 2001) and the X-ray flux of the 2005 outburst (Zurita et al. 2006) was about 20% lower, they were well below the Eddington limit. Viscous heating of the ionized disk thus played a big role. The mutual similarity of the outbursts in Figure 3 speaks in favour of a similar such X-ray luminosity and the viscous heating also in the 1927 outburst.

The different lengths of the viscous plateaux in the individual outbursts of KV UMa can be caused by the differences in the accumulation of matter in the quiescent disk (Matthews et al. 2007). In the interpretation, since the 2005 outburst was considerably shorter than the 2000 main outburst, the amount of the disk mass able to switch to the ionized state with the tidal instability was considerably lower, possibly because of the variations of the radial distance from the compact object in which the inflowing matter predominantly accumulated [model of Schreiber & Hessman (1998)]. In this framework, the amount of the ionized disk matter in the 1927 outburst was intermediate between the 2000 and 2005 events. In the case of KV UMa, a very strong magnetic activity of the donor (González Hernández et al. 2012; Zurita et al. 2016) may play a role in influencing the disk dimensions and its mass distribution in quiescence, modifying thus the disk mass and the time needed for transition of the disk to the hot state.

In the context of the TTI, precursors are also part of the long-term activity of some SU UMa dwarf novae (Marino & Walker 1979; Warner 1995). Although the peak magnitude of such a precursor is roughly comparable to that of the superoutburst, the time interval between these events can significantly vary (Marino & Walker 1979; Warner 1995). VW Hyi is an example that not every superoutburst must have its precursor.

If O1 were a precursor to a main outburst like the ones detected in 1927 or 2000, then the upper limits of brightness spanning between O1 and JD 2 427 938 would suggest an interval of 155 d between the precursor and the main outburst. The subsequent gap of 221 d in the data would be able to accommodate even the 2000 main outburst. Alternatively, KV UMa is able to launch also short isolated outbursts. The time interval between the 1927/1928 main outburst and a subsequent main outburst is therefore longer than 5 yr. Also O2 may be a short isolated outburst. Although O2 was situated in the X-ray astronomy era, even if it were a real event accompanied by an increase of the X-ray flux comparable to the 2005 outburst (Zurita et al. 2006), it was improbable to detect it because even the X-ray flux of the 2005 event was only slightly above the detection limit of ASM/ *RXTE* (Levine et al. 1996).

Vogt (1993) shows that the number of normal outbursts between two superoutbursts of the SU UMa dwarf novae varies significantly, from about 10 even to 0. Using analogy with the SU UMa dwarf novae, we attribute the paucity of normal outbursts in KV UMa to the relation of Patterson et al. (1995) (their Figure 18); the recurrence time of normal outbursts increases faster than the recurrence time of superoutbursts. This places KV UMa in the region of the recurrence times in which the number of normal outbursts is very low.

The jet contribution to the optical and near infrared was similar in the 2000 and 2005 outbursts (more in the infrared and radio than the V and the B-bands) (Hynes et al. 2006). The time evolution of the optical outbursts (along with the 1927 outburst) (Figure 3) must have been dominated and governed by thermal emission of the accretion disk. In other case, no superhumps would be detected. Since the optical magnitude and profile of the optical light curve of the 1927 outburst are similar to those of the 2000 and 2005 outbursts, this speaks in favour of thermal emission playing a big role in the optical band in all three outbursts. The transition from stage P to stage F occurred at a very similar optical brightnesses no matter how large the contribution of the jet was. This also suggests that also the decaying branch in stage F was dominated by thermal emission and propagation of cooling front.

We can also place the observed time intervals between the outbursts of KV UMa in the context of the recurrence times of the outbursts of SXTs. The BH SXT V616 Mon (Haswell et al. 1993) displayed the optical outbursts in 1917 (Eachus et al. 1976) and 1975 (Wu et al. 1976), so the recurrence time was 58 yr. Another such BH SXT, V404 Cyg (Casares et al. 1992), displayed the optical outbursts in 1938, 1956, 1989 and 2015 (Wagner et al. 1989; Richter 1989; Barthelmy et al. 2015; Oates et al. 2019). Its recurrence time is therefore between 18 and 33 yr. The BH SXT V518 Per (GRO J0422+32) (Beekman et al. 1997) underwent its main outburst in 1992, followed by two minor outbursts (Shrader et al. 1994). This SXT has been in quiescence since 1994. On the other hand, a considerably shorter recurrence time of the outbursts of the BH SXT (Parmar et al. 1986), 4U 1630-47 (Kuulkers 1998), varies between 601 and 682 d (Kuulkers 1998). The neutron-star SXT, Aql X-1 (Koyama et al. 1981), displays the optical outbursts with the recurrence time of about 1 yr (Maitra & Bailyn 2008). The lengths of the recurrence times of these SXTs thus display a very broad range and can significantly vary even in a given SXT. Various profiles of the light curves of their outbursts can suggest various roles of irradiation of the disks in outburst [e.g., models of King & Ritter (1998) and Dubus et al. (2001)]. In this framework, the variations of the recurrence time of the outbursts of KV UMa are comparable to them even if some of these events were missed.

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