Mem. S.A.It. Vol. 83, 238

Memorie della

Optical monitoring of binary X-ray sources

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Abstract. We review the long-term activity of optical counterparts of binary high energy sources (high- and low-mass X-ray binaries, cataclysmic variables of various types including supersoft X-ray sources (SXSs)). Their activity on long timescales remains little studied, although it is very important for our understanding of the relevant physical processes. The optical emission is detectable by the ground-based telescopes, therefore the activity of some of these sources has been mapped for several decades. An increase of the mass accretion rate onto the compact object leads to an increase of the optical luminosity. However, an X-ray brightening does not always occur; this is often the case of dwarf novae and SXSs. During matter exchange, episodic events often occur. The systems tend to display the discrete levels of intensity and/or discrete phenomena (e.g. outbursts, low state episodes). The individual events differ from each other even in the same system. The long-term transition of the character of activity in a given system is sometimes observable even in the available data. However, it does not mean that we observe the evolutionary changes in the real time.

Key words. X-rays: binaries – circumstellar matter – accretion, accretion disks – novae, cataclysmic variables – Radiation mechanisms: general

1. Introduction

In the binary systems which contain mass-accreting compact objects, i.e. white dwarfs (WDs), neutron stars (NSs), and black holes (BHs), matter flows onto the compact object from a companion star, the so-called donor. These systems are abbreviated as cataclysmic variables (CVs) if they contain a WD, and X-ray binaries ('high mass X-ray binaries' (HMXBs) or 'low mass X-ray binaries' (LMXBs)) if they contain a NS or a BH. They are often active in real time over a very broad range of timescales, from seconds to decades, not speaking about their evolutionary changes. They are therefore very important laboratories for the study of physical processes. Reviews of these systems can be found in e.g. Lewin et al. (1995), Lewin & van der Klis (2006), and Warner (1995).

These binaries radiate in a very broad range of wavelengths, from X-ray (or even gamma-ray), through UV to the optical, IR, or even the radio bands. This mass-transferring binary is a complicated and very active system. Their activity on long time scales remains little studied, although it is very important for our understanding of the relevant physical processes. The optical emission is detectable by the ground-based telescopes, therefore the activity of some of these sources has been mapped for several decades, in some extreme cases even for more than a century.

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2. Types of X-ray binaries and their optical activity

2.1. High-mass X-ray binaries (HMXBs)

The mass-donating star (donor) of early spectral type (O, B) emits thermal radiation (UV, optical, IR) and is often dominant in the optical band. The accretion disk embedding the compact object may exist in some systems. The spectral band in which it is detected differs from system to system. The close vicinity of the compact object is often the dominant emitter of X-rays. Also colliding winds can emit part of X-ray emission. Jets (relativistic outflows of matter), observed in some systems, radiate via synchrotron process in radio.

HMXBs were found to display several accretion modes. If the donor fills its Roche lobe, then the mass transfer occurs via lobe overflow. In systems with the donor underfilling its lobe, wind accretion or enhanced mass accretion during periastron passage can occur.

We show several examples of the optical activity of HMXBs.

CI Cam/XTE J0421+560 is a remarkable system. It consists of the supergiant B[e] donor and the BH (e.g. Robinson et al. 2002; Hynes et al. 2002). The orbital period $P_{\rm orb}$ is 19.407 d (the eccentricity of 0.62) (Barsukova et al. 2006). The unique outburst occurred in 1998 (Frontera et al. 1998) and attracted attention to this system, not supposed to be a binary before. During this event, intense X-ray emission was accompanied by the optical (about 2 mag(V)) and radio brightening. Supercritical accretion occurred during the peak of this outburst (Hynes et al. 2002; Shakura & Sunyaev 1973). The outburst was interpreted as being due to a thermal-viscous instability of a small, wind-fed accretion disk, analogous to outbursts of soft X-ray transients (Šimon et al. 2006).

The activity of CI Cam continued even after the outburst. The variations of the color indices in the optical band in quiescence suggested the presence of several superimposed spectral components produced by and belonging to the donor (Clark et al. 2000; Šimon et al. 2007). No changes of reddening intrinsic to this system were observed. Huge changes of extinction in X-rays (Parmar et al. 2000; Boirin et al. 2002) and no extinction variations in the optical suggest that the X-ray emission comes from the close vicinity of the mass-accreting BH, not from the giant donor. Re-filling of the accretion disk after the outburst can explain this behavior.

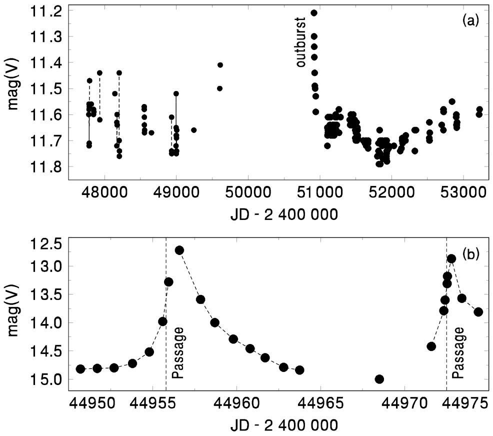

Fig. 1. (a) The long-term activity of CI Cam. The peak of the 1998 outburst is out of scale. Adapted from Šimon et al. (2007) and Šimon (2010a). (b) One orbital cycle of A0538–66 with the large-amplitude brightenings during periastron passage. Adapted from Densham et al. (1983).

Part of the long-term optical activity (1985–2004) is shown in Fig. 1a (see Šimon et al. (2007) and Šimon (2010a) for more). The 1998 outburst dramatically influenced the system. Notice the striking difference in activity before and after the outburst. After return to quiescence, the brightness variations became significantly more gradual and with a lower amplitude. Bamberg photographic light curve in the blue band (1928–1939) displayed the character of activity similar to that in Fig. 1a before the outburst. It thus appears that even the optical activity itself of such a unique system can indicate the influence of the X-ray outburst on the character of the long-term activity. In this framework, the outbursts of CI Cam thus appear to be very rare (one event per several decades?).

A0538–66 is a recurrent X-ray transient in the Large Magellanic Cloud (White &

Carpenter 1978) which underwent dramatic changes of its optical activity during the last decades. It consists of a massive Be donor ($\sim$ 12 $M_\odot$) (Charles et al. 1983) and the NS (Skinner et al. 1982). Its $P_{\rm orb}$ is 16.65 days (Skinner 1981).

In 1981 and 1982, A0538–66 underwent a series of intense outbursts which were caused by periastron passages of the NS in a highly eccentric orbit ($e \sim 0.7$), hence by episodes of a dramatically increased mass accretion rate onto it (Charles et al. 1983; Densham et al. 1983) (Fig. 1b). Super-Eddington luminosity occurred at the outburst peak ($L_{\rm X} \approx 10^{39}$ erg s^{-1}) (Charles et al. 1983). During this event, the continuum came from the emitting region several times the size of the donor. At periastron, the donor overfilled its tidal lobe, which provided a large increase in mass transfer to the NS (Charles et al. 1983). However, these huge outbursts represented only a short episode in the photometric history of this system. Archival plate data (from 1915 April to 1981 July), albeit with non-uniform coverage, revealed a gradually declining level of brightness by about 1.5 mag(B) (McGowan & Charles 2003). The 421-d cycle, interpreted as the formation and depletion of an equatorial disk embedding the donor, was superimposed on this decline (McGowan & Charles 2003; Alcock et al. 2001). Generally, this cycle with the peak-to-peak amplitude Δ of about 0.5 mag(V) dominates except 1981–1982. This Δ is comparable to or larger than that of the periastron outbursts. The season 1981–1982 was thus a period of exceptional activity with huge outbursts. It suggests a transient change of the close environment of the donor.

V725 Tau/A0535+26 contains an O9.7IIIe donor and the NS (Giovannelli & Graziati 1992). Its $P_{\rm orb}$ is 111 days (Warwick et al. 1981). Giovannelli & Ziolkowski (1990) argued in favor of double-disk system. X-ray outbursts, accompanied by small optical brightenings ($<$ 0.1 mag(V)), occur only in some periastron passages (Guarnieri et al. 1985). Their occurrence is modulated by the phase of the $\sim$ 1500-d period ($\Delta \approx 0.3$ mag(V)) which may be due to precession of the Be disk (Haigh et al. 2004). Evolution of the optical activity during about 90 years (Giovannelli et al. 1988; Giovannelli & Graziati 1992) displayed the segments in which the fluctuations of brightness similar to those reported by Haigh et al. (2004) were present. In seasons of increased brightness, each of them lasting for several years, these fluctuations disappeared. In this framework, the disk precession is a transient phenomenon.

SS433 is a very massive microquasar (Mirabel & Rodríguez 1999) ($M_{\rm donor}$ = 35 $M_\odot$, $M_{\rm BH}$ = 20 $M_\odot$) with a big accretion disk embedding the BH accretor (Lopez et al. 2006). Monitoring during 1979–1981 (Gladyshev et al. 1983) revealed several superimposed types of variability with the combined $\Delta \approx 1.5$ mag(V): orbital modulation ($P_{\rm orb}$ = 13.1 d Crampton et al. 1980), flares, and precession cycle of the accretion disk (164 d Crampton & Hutchings 1981).

2.2. *Low-mass X-ray binaries (LMXBs) and cataclysmic variables (CVs)*

LMXBs and CVs contain a compact object which accretes matter from the Roche lobe-filling donor. The type of donor depends on $P_{\rm orb}$ ranging from several minutes to several days. In most systems, the accretion proceeds via the accretion disk. In many cases and spectral bands, the dominant part of luminosity originates from the transferring matter, not from the stellar components. The accretion process is thus the dominant source of their luminosity.

2.2.1. Systems with outbursts

In some systems, the accretion disk suffers from a thermal-viscous instability if the mass transfer rate $\dot{m}$ lies between certain limits. It gives rise to the large-amplitude (even more than 5 mag) outbursts in CVs called dwarf novae (DNe) (e.g. Hameury et al. 1998) and LMXBs called soft X-ray transients (SXTs) (e.g. Dubus et al. 2001). The typical duration of outburst is from several days (in some DNe) to weeks and months (mostly in SXTs).

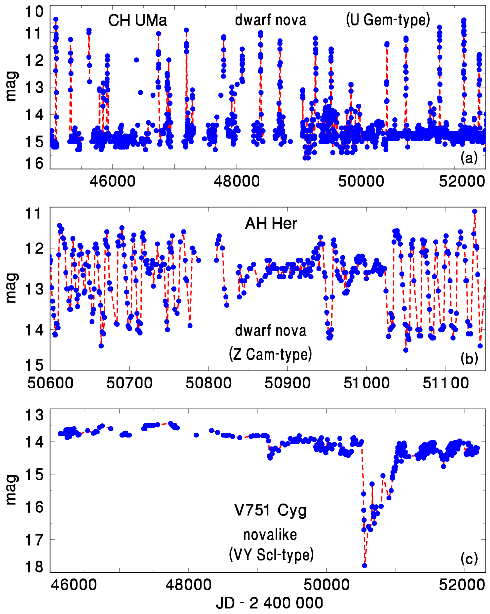

Fig. 2. Systematics of cataclysmic variables. The types are arranged according to the increasing time-averaged $\dot{m}$: (a) thermally unstable accretion disk, (b) disk balancing between thermally stable and unstable state, (c) thermally stable disk (for most time). One-day means of AFOEV data were used.

Since most available observations of SXTs are in the X-ray band, it is necessary to assess the relation between the X-ray and optical luminosity. A correlation between the X-ray and optical luminosities exists at least when large changes of luminosity are considered (Russell et al. 2010). The scatter in this relation is due to several reasons like the fact that the optical luminosity comes from the different region of the system than the X-ray one, the different absorption of X-rays inside the individual LMXBs, the role of reprocessing off X-rays, size of the accretion disk, and outflow of accreting matter from the inner disk region.

V1333 Aql/Aql X-1 is an important SXT with frequent outbursts (their typical recurrence time T_C is about 330 d). It was monitored in both the optical and soft X-ray bands for several years (Maitra & Bailyn 2008). This case shows that monitoring is necessary to build a representative ensemble of outbursts in a given system. It emerged that the relation between X-ray and optical luminosity differs substantially for the individual outbursts. This relation can even display episodes of largely different values in a single outburst. This can be explained by fundamentally different accretion flow properties. Maitra & Bailyn (2008) suggested the role of truncation of the inner disk region in the state of a relatively high mass accretion rate, possibly due to matter being diverted into a weak outflow.

QX Nor/4U 1608–52 is an SXT with peculiar long-term activity and a strange relation between the X-ray and optical luminosity (Wachter et al. 2002). In addition to the usual X-ray outbursts accompanied by the brightenings by about 2 mag and quiescent states, it displays extended low-intensity states in which the optical counterpart is by about 1 mag brighter than during the true quiescence. Such states suggest the presence of a luminous accretion disk. Some smaller X-ray outbursts starting from these low-intensity states may not have optical counterpart – the system is already brightened in the optical even outside the X-ray outburst. It is difficult to understand the low-intensity state and true quiescence in the context of the pure thermal instability model that describes the SXT phenomenon as a limit cycle between two discrete disk states (Wachter et al. 2002).

An unexpected optical activity was observed in the SXT system *BW Cir/GS 1354–64* in quiescence after the end of its X-ray and optical outburst (Casares et al. 2009). Its character can be described as fluctuations with an amplitude of about 1 mag. The nature of these fluctuations is unclear (smooth waves, small outbursts?). At least some SXTs are thus not dormant in quiescence. This phenomenon represents a new perspective for monitoring of SXTs in various spectral regions in quiescence.

The role of monitoring of SXTs is emphasized by the fact that some systems display the so-called echo outbursts. *SAX J1808.4–3658* is an example (Wijnands 2006). These events are a series of episodic brightenings (about 1 mag in the optical) even during several months after the end of the main outburst. They appear to be related to the thermal instability of the disk, not to the donor (Hellier 2001; Šimon 2010b). The relation between the optical and X-ray intensity is uncertain.

Can we detect synchrotron jets of X-ray binaries in the optical band? These jets are usually considered to radiate in the radio band, but since the optical monitoring is definitely more feasible than the radio one, it is reasonable to try this optical search. In the optical, the color index of the jet is expected to be redder than that of the hot accretion disk. Indeed, short flares, accompanied by episodes of anomalous color indices, superimposed on the gradually evolving light curves of some outbursts were observed in two SXTs, Aql X-1 (Charles et al. 1980) and SAX J1808.4–3658 (Greenhill et al. 2006).

It is possible to arrange the individual types of CVs with their very complicated long-term activity in a sequence according to the increasing time-averaged $\dot{m}$, hence also according to the increasing time-averaged optical luminosity (e.g. Warner 1995) (Fig. 2). This means the change of activity from large-amplitude, rare and isolated outbursts starting from the faint quiescent state to the more frequent outbursts, and finally to the thermally stable disk with the optical luminosity roughly corresponding to the peak of outburst. A similar sequence may also exist for LMXBs, but the optical data are yet too sparse.

SS Cyg/3A 2140+433 is a well-known DN, monitored for about a century. It displays two types of outbursts as regards their energy output and duration. Some relation between the quiescence level and T_C of outbursts appears to exist. This level is fainter in the vicinity of outbursts which have a longer T_C. This can be explained by the long-term (years) fluctuations of $\dot{m}$ from the donor. Although the outbursts themselves are caused by the thermal-viscous instability of the disk, the conditions for this instability are modulated by the donor (Cannizzo & Mattei 1992). A complicated relation between the optical and X-ray profile exists. Boundary layer changes from optically thin, geometrically thick to optically thick, geometrically thin during outburst (Wheatley et al. 2003).

GK Per/1A 0327+43 is a very remarkable CV as regards its dramatic variations of type during only several decades. This system exploded as classical nova in 1901. It underwent a transition between the CV types during less than a century: classical nova – novalike – dwarf nova (Sabbadin & Bianchini 1983). DN outbursts brightened and their T_C increased from 385 days during the years 1948–1967 to more than 1000 days at present (Sabbadin & Bianchini 1983; Hudec 1981a; Šimon 2002) (Fig. 3a). Evolution of the annular means of the photographic brightness of GK Per (i.e. brightness averaged over DN outbursts) (Hudec 1981a) shows that the change of type coincides with a decrease of the system's optical output (Fig. 3b).

A slow decrease of the effective temperature of the WD after the end of nova explosion appears to be the main common cause of this activity of GK Per. This lead to a decrease of irradiation of the disk by the WD. The disk thus became thermally unstable (Schreiber et al. 2000). This decrease of irradiation, combined with a decrease of the disk viscosity in quiescence, influenced the conditions for the thermal instability of the accretion disk. Variations of $\dot{m}$ are unlikely to play a major role (Šimon 2002).

Some CVs were observed to display brief brightenings which cannot be explained by a thermal-viscous instability. The intermediate polar *V1223 Sgr* is an example. Three such flares were detected. van Amerongen & van Paradijs (1989) found that the optical outburst with the amplitude of more than 1 mag lasted only for several hours. The flare in the Hα line was longer than in the continuum, which suggests that also the line emission participated in this event. Other flare with the amplitude of more than 1 mag was found on the archival plate (Šimon 2010a). This event occurred during a shallow low state, but still from the level by several magnitudes brighter than the true low states (Garnavich & Szkody 1988). The third flare was observed in far infrared (14–21 μm). The flux declined by a factor of 13 in

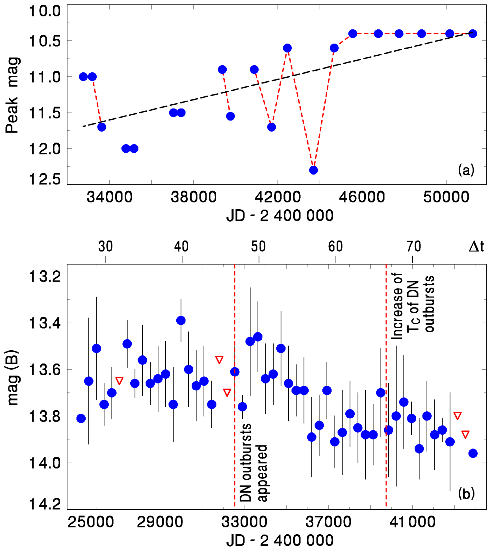

Fig. 3. (a) Evolution of the peak magnitude of DN outbursts in GK Per. A linear fit is marked by the dashed line. Adapted from Šimon (2002). (b) Evolution of the annular means of the photographic brightness of GK Per. The time elapsed from nova explosion is marked as Δt (in years). Adapted from Hudec (1981a).

30 minutes. It suggests a transient synchrotron emission of the flare (Harrison et al. 2010).

2.2.2. Systems without outbursts

Even the systems with the high time-averaged $\dot{m}$, hence with their hot, thermally stable disks, display strong activity.

HZ Her/Her X-1 is a LMXB which usually displays long-lasting active states. The dominant part of the optical emission in this state is caused by reprocessing off X-rays (coming from the close vicinity of the NS) on the photosphere of the lobe-filling donor (Gerend & Boynton 1976). This results in the orbital modulation with a big amplitude. Occasional episodes of inactive state lead to a remarkably different profile of the orbital modulation, which can be explained by a decrease of irradiation of the donor. These states occurred before the start of the era of X-ray observing (Hudec & Wenzel 1976).

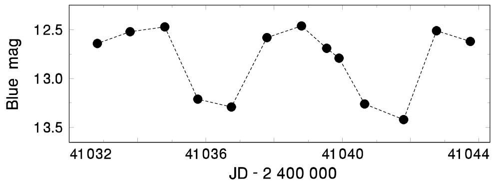

Fig. 4. Schematic view of the high/low state transitions in Sco X-1 (mostly night means). Adapted from Bradt et al. (1975).

V818 Sco/Sco X-1 is a persistent LMXB. Simultaneous observations of the X-ray, optical, and radio activity mapping the behavior in several nights showed that the fluxes in these bands are not strictly correlated (Bradt et al. 1975) (Fig. 4). The relation between the X-ray and optical changes is caused by the shifts in the X-ray color-color diagram of the ‘Z’ source (Augusteijn et al. 1992). Sco X-1 displays several types of the optical activity: the orbital modulation ($P_{\rm orb}$ = 0.787 d Gottlieb et al. 1975), night-to-night fluctuations, high/low state transitions on the timescale of days (Fig. 4). In addition, the system undergoes variations of the mean brightness on the timescale of years and decades (Wright et al. 1975; Hudec 1981b). The differences in the B-mag histograms made for the individual years were explained by McNamara et al. (2003) as the variations in the mass accretion rate and the relatively short time period typically covered by optical observations.

KR Aur/2E 0612.5+2836 is a novalike system. It displayed a series of high and low states. Honeycutt & Kafka (2004) interpreted the low states as due to a spot drifting underneath the L1 point on the donor. In this framework, the steep portion of the transition was caused by the umbral portion of the spot. The less steep portion was due to the penumbra of the spot.

V Sge/2E 2018.0+2056 is supersoft X-ray binary source (SXS). Such objects are unique binary systems in which the mass transfer onto the WD occurs at a very high rate ($\dot{m} \approx 10^{-7}\ M_\odot\ {\rm yr}^{-1}$). This allows a steady-state hydrogen burning on the WD (van den Heuvel et al. 1992). Intense soft X-ray emission is produced, but its detectability depends on the

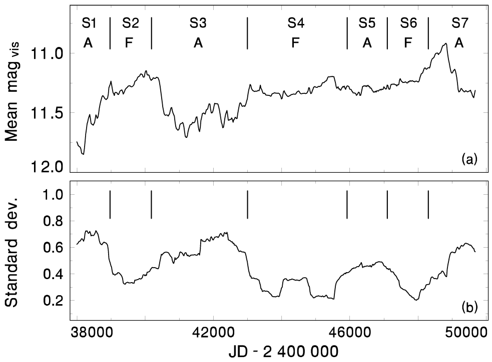

Fig. 5. Evolution of the moving averages of the wild optical variations in V Sge. Active and flat segments are marked as A and F, respectively. Adapted from Šimon & Mattei (1999).

interstellar extinction and metallicity of the source. The optical emission comes from both the reprocessing off X-rays in the disk and from the disk viscosity.

V Sge displays a very complicated long-term optical activity. Intervals of the suppressed brightness variations (flat segments) interchange with intervals of the pronounced changes (active segments) (Šimon & Mattei 1999) (Fig. 5). The low level of brightness of the active segment gives rise to the relatively separated outbursts while the high state/low state transitions occur in segments with a higher mean brightness. The character of activity changed considerably during about 40 years. The optical luminosity is in antiphase with soft X-ray luminosity due to an increase of X-ray absorption (Greiner & van Teeseling 1998). The features of activity were interpreted in terms of accretion wind evolution by Hachisu & Kato (2003).

3. Conclusions

The optical changes caused by the variations of $\dot{m}$ occur in various kinds of X-ray binaries. It is important that the binary works as a system. The amount of $\dot{m}$ depends on the processes operating in the donor; the degree of filling the lobe, type of donor, and coverage of the donor by starspots play an important role in this regard. Formation and structure of an envelope around the donor appear to be especially crucial in HMXBs. Also a configuration of the transferring matter and existence (and state) of the accretion disk determine the long-term activity of the system.

An increase of the mass accretion rate onto the compact object leads to an increase of the optical luminosity. However, the X-ray variations are complicated and the X-ray brightening does not always occur – this is often the case of DNe and SXSs. It is also interesting to note that reprocessing off X-ray emission on the donor enables us to discover that X-ray emission is produced in the binary even if its X-rays are not directly observable due to X-ray absorption inside the source (e.g. Her X-1) (e.g. Maloney & Begelman 1997).

The amplitude of the observed optical outburst depends on the type and optical luminosity of donor. Since the donor often dominates the optical output of HMXB, only the very intense episodes (with the luminosity comparable to the Eddington one) of the mass accretion onto the compact object can usually lead to the increase of brightness by about 1 mag.

During matter exchange, episodic events often occur. The systems tend to display the relatively discrete levels of intensity and/or discrete phenomena (e.g. outbursts, low state episodes). The individual events differ from each other even in the same system.

A long-term transition of the character of activity in a given system is sometimes observable even in the available data. This gives us the possibility to search for and to achieve some degree of unification. In some cases, it is even possible to find some triggers. The case of GK Per is remarkable. Its classical nova explosion started a dramatic change of activity in the subsequent decades after return to quiescence. However, it does not mean that we observe the evolutionary changes in the real time in these objects. Our observations rather map some cycles of activity.

Acknowledgements. Support by the grant 205/08/1207 of the Grant Agency of the Czech Republic is acknowledged. This research has made use of the observations from the AFOEV database operated in Strasbourg, France.

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