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*Review Article*

# Monitoring of X-Ray Sources in the Optical Spectral Region

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We review current results and perspectives of the photometric monitoring of the optical counterparts of X-ray sources of various kinds (binary X-ray sources (cataclysmic variables and low-mass X-ray binaries, supersoft X-ray sources, microquasars), gamma-ray bursts). We discuss the problems of the monitoring of the individual kinds of objects in the optical and X-ray passbands. We show the importance of multifilter monitoring to obtain a deeper understanding of the physical processes and to resolve between the individual emission mechanisms. We also show that there are brief, unique, and little understood phenomena which are very promising targets for the optical monitoring, for example, flares in intermediate polars.

## 1. Introduction

This review deals with the observations of the optical counterparts of sources of high-energy emission. Since the research field of the high-energy sources is already very broad, we have to limit this topic. We will concentrate on the systems which contain a compact object with the mass comparable with the stars, that is, excluding supermassive black holes present in active galactic nuclei. Furthermore, we will concentrate on the systems and events in which the optical emission radiated by the accreting matter dominates. Our review is focused on binary X-ray sources (cataclysmic variables (CVs), low-mass X-ray binaries (LMXBs), supersoft X-ray sources, microquasars), gamma-ray bursts (GRBs). These objects are very important laboratories for the study of the physical processes occurring in extreme conditions. However, their activity on long timescales of months, years, and even decades remains little studied, although it is very important for our understanding of the relevant physics. A search for and analysis of rare dramatic variations of activity like outbursts of various kinds which reflect huge changes of the physical processes are particularly exciting.

Study of the long-term activity requires monitoring of the individual objects (if they are already identified), or even monitoring of the large fields of the sky to search for the events like optical afterglows of GRBs.

## 2. Binary X-Ray Sources

CVs and LMXBs are binary systems in the phase of mass exchange (e.g., [1, 2]). They contain a compact object (white dwarf in CVs, neutron star, or black hole in LMXBs) which accretes matter from its Roche lobe-filling companion (the so-Called donor). The donor is usually a late type main-sequence star, but also rare cases where it is a subgiant or a white dwarf are known (the type of the donor depends on the orbital period ranging from several minutes to several days, mostly several hours). These systems are emitters of radiation over a very broad range of wavelengths, from high energy (X-ray, sometimes even gamma-ray) to the optical and infrared, in some cases even to the radio. In most cases and spectral passbands, the luminosity of these systems is dominated by the light originating from the transferring matter, not from the stellar components. The accretion process is thus the dominant source of their luminosity. These systems are extremely active in real time over a very broad range of timescales, from seconds to decades, not speaking about their evolutionary changes. This activity is directly related to the physical processes in the transferring matter and its accretion onto the compact object.

*2.1. Mechanisms for the Long-Term Activity in CVs and LMXBs.* Several mechanisms can cause the long-term variations of brightness in CVs and LMXBs (e.g., [1]).

(a) Changes of the mass transfer rate $\dot{m}$ from the donor onto the compact object. They occur on the timescale of days, weeks, months, and years. They give rise to the luminosity of the accretion disk and hence to the fluctuations of the brightness of the system, including the transitions between the high and low states in both CVs and LMXBs. The amplitude of these variations can be several magnitudes.

(b) Thermal-viscous instability of the accretion disk. It gives rise to the outbursts in CVs and LMXBs. These outbursts have the typical optical amplitudes between 2 and 5 mag in CVs called dwarf novae and between 3 and 7 mag in LMXBs called soft X-ray transients (SXTs). The typical recurrence time $T_C$ (cycle-length) of these outbursts is weeks and months in dwarf novae. However, it is often years and decades in the case of SXTs. The typical length of the outburst is days and weeks in dwarf novae, but weeks and months in SXTs.

(c) Hydrogen burning on the white dwarf. Episodic burning leads to the classical nova explosion. The amplitude of the explosion is very high, about 12 mag, with the duration of the event being from weeks to months. Steady-state burning is thought to explain supersoft X-ray sources (a unique type of CVs with a very high $\dot{m}$ [3]). Such objects are also luminous in the optical passband. Some of them undergo fluctuations of brightness and high/low state transitions with the amplitude of 1–2 mag on the timescales of weeks and months.

This very brief overview of the mechanisms clearly shows that CVs and LMXBs with their wild activity are very attractive targets for the monitoring. Some of these variations and events may be cyclic, but they are not periodic. In additions, dramatic changes of the activity on the timescale of years and decades were observed in some systems, so our understanding of a given object can hardly be satisfactory if the physical processes which control its long-term activity are not taken into account.

*2.2. Problems in the Long-Term Coverage.* The different X-ray/optical intensity ratios of the individual categories of binary X-ray sources impose problems on the long-term coverage of their activity.

LMXBs are often bright in X-rays at least in their outburst. Several tens of them are easily observable by the X-ray monitors onboard the satellites, but they are often faint in the optical passband. They are usually fainter than 16–18 mag except infrequent outbursts, so the existing optical data are often fragmentary or even absent.

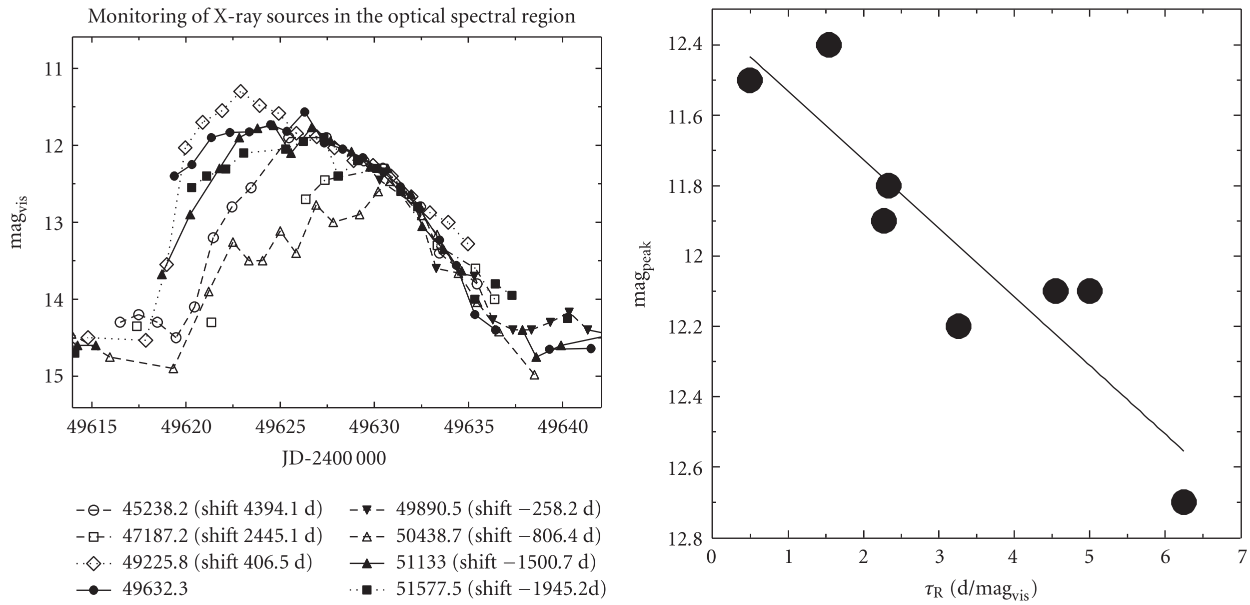
CVs are often relatively bright in the optical passband, so good long-term coverage is available at least for some of them. Nevertheless, more deep observations are needed in quiescence between outbursts and in the episodes of the low state, since the brightness of some of these systems is below the detection limit of the usually used visual observations in these states of activity. The X-ray data of CVs are often fragmentary because most of these systems are too faint for the X-ray monitors.

Transitions between the activity states (e.g., outbursts, high/low state transitions) are often fast and unpredictable. Monitors are thus needed to resolve them. Occasional pointing is not enough because of several reasons: many pieces of information on the time evolution are lost; time allocation has to be justified (search for unexpected behavior of the object is usually not approved).

*2.3. Properties of the Outburst Light Curves in Dwarf Novae.* Investigation of any more general properties of outbursts in dwarf novae deserves coverage of several outbursts in a given binary. Monitoring is necessary to obtain a sufficient number of the well-mapped outbursts to collect a meaningful ensemble of outbursts. The typical duration of the outburst is from several days to one or two weeks, while the recurrence time $T_C$ of outbursts is from several weeks to several months, although exceptions exist (e.g., [1]). A single observation per night may thus be sufficient to cover the profile of outburst, although denser coverage is desirable for the often steep rising branch. The case of DX And can serve as an example of the long-term activity [4] (Figure 1(a)). The peak magnitude of outbursts turns out to be variable by 1.3 $\text{mag}_{\text{vis}}$. While the slope of the rising branches of the outbursts was found to be largely dependent on the peak magnitude (brighter outbursts having steeper rises), the decaying branches remain stable and very similar for most outbursts. Shifting the individual outbursts along the time axis to match the decay branch of the template then enabled to investigate the properties of the profiles of the light curves of the ensemble. The relation between the peak magnitude of the outburst and the slope of its rising branch (Figure 1(b)) can thus be established. This can be used for testing the thermal-viscous instability model (e.g., [5]), particularly for the discrimination between the case A (outside-in) and case B (inside-out) outbursts.

The determination of the location where the outburst starts, that is, case A versus case B event, is important for the study of the physics of outbursts in a large ensemble of dwarf novae with various system parameters like the orbital period, and so forth. Clearly, the outbursts in more systems have to be studied in a similar way as DX And.

The magnetic field of the white dwarf in intermediate polars (CVs with a magnetized white dwarf (e.g., [1])) can influence the profile and recurrence time (cycle-length) $T_C$ of their outbursts caused by the thermal-viscous instability [7]. This results in short and infrequent outbursts like in DO Dra (e.g., [8]). It is thus quite possible that many such outbursts in CVs which may be intermediate polars remain unobserved due to insufficient coverage by the data. Clearly, more attention to monitoring of intermediate polars and the




(a) (b)

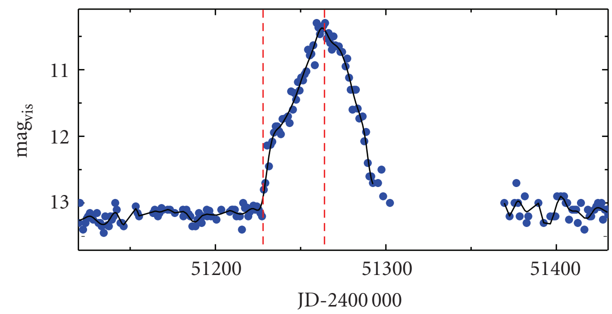
FIGURE 1: (a) Profiles of the outbursts in the dwarf nova DX And (observations from the AFOEV database). One-day means were connected by a line in densely covered parts for convenience. The individual outbursts were shifted along the time axis to match the decaying branch of the template—the time of crossing 12.8 mag$_{vis}$ and the shifts with respect to the template are listed. (b) The relation between the peak magnitude mag$_{peak}$ of the outburst and the slope of its rising branch in DX And. The slope (rate of rise $\tau_R$) is expressed in days mag$_{vis}^{-1}$. Adapted from [4].

investigation of the properties of their outbursts should be paid.

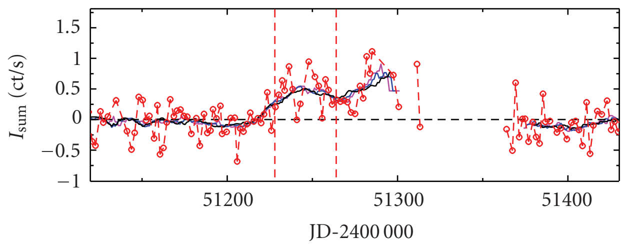
Some dwarf novae display the cyclic variations of the brightness in quiescence, with the typical cycle-length of several years, which was attributed to the solar-type cycles of activity of the donor [9]. The typical brightness of many dwarf novae in quiescence ~14–17 mag(V) enables to monitor such systems and to investigate these variations and their relation to the outburst parameters.

The state of the long-term activity of at least some CVs is affected by their classical nova explosions. The large influence of these events can be apparent even decades after the explosion. At least some CVs which were observed to explode as classical novae display a complicated evolution of their activity after return to quiescence. The intermediate polar GK Per (Nova Per 1901/A 0327+43) [10] is an important example in this regard (e.g., [6, 11, 12]). Fluctuations of its brightness by about 1 mag on the timescale of months appeared after return to quiescence. Later, they developed into the discrete 2-3 mag optical outbursts which recur on timescales of hundreds of days. Their amplitude and recurrence time tend to increase. A similar behavior is observed in V446 Her (Nova Her 1960) [13]. The behavior of such systems can be caused by the decrease of the temperature of the white dwarf in the decades following the nova explosion. The irradiation of the disk by the very hot white dwarf helps the disk remain in the hot, luminous state, so no outbursts occur. The cooling of the white dwarf can lead to the evolution of the thermal-viscous instability of the disk and to the appearance of the outbursts.

Current results show that the relation between the profiles of the outburst of dwarf nova in the optical and X-ray passbands is very complicated, as shown by the pointed observations of SS Cyg by [14, 15]. Such studies of a larger ensemble of dwarf novae are important because these multifrequency observations enable us to investigate the behavior of various parts of the system; X-rays come from the close vicinity of the white dwarf, while the optical emission originates from a large area of the accretion disk. Indeed, the observations of [14, 15] show that the boundary layer changes from the optically thin, geometrically thick to the optically thick, geometrically thin during outburst. However, the problem is the low ratio of the X-ray to the optical intensity of many CVs and the complicated variations of the X-ray intensity during outburst. Only a very few CVs were detected by the X-ray monitor ASM/RXTE. The X-ray intensity of SS Cyg in the 1.5–12 keV passband of ASM/RXTE decreases below its quiescent level during outburst [16]. The X-ray intensity of GK Per observed by this instrument rises only slightly during the optical outburst, and the profile of the X-ray and optical light curve largely differ from each other in the time of the peak optical brightness [6] (Figure 2). The start of the X-ray outburst can precede the start of the optical one by up to 40 days [17, 18]. Figure 2 shows the optical and X-ray profile of a well-mapped outburst. The optical data used for Figure 2(a) were fitted by the code HEC13 written by [19]. The code is based on the method of [20, 21]. This method can fit a smooth curve to the data no matter what their profile is. The resulting fit consists of the mean points, calculated to the individual observed




(a)




(b)

Figure 2: Relation between the outburst light curves of GK Per in the optical (a) and X-ray (1.5–12 keV) (b) passbands. The optical data are from the AFOEV database, while the X-ray ones were obtained by ASM/RXTE. The smooth line in (a) represents the fit by the code HEC13. The thick lines in (b) denote the smoothing by the moving averages. The dashed vertical lines mark the times of the onset and the maximum light of the outburst in the optical region. Adapted from [6]. See Section 2.3 for details.

points of the curve. A set of fits to the data with the different input parameters $\epsilon$ and $\Delta T$ was generated and submitted to inspection. It was found that the fit with $\epsilon = 0.1$, $\Delta T = 5$ d reproduces the main features of the light curve and enhances the visibility of the main profile. It is true that this method is somewhat subjective but it enables us to find a compromise between a curve running through all the observed values and an ideal smooth curve. The X-ray signal in Figure 2(b) was smoothed by the moving averages with the filter half-widths of 10 d, 12 d, and 15 d. They reproduce the main features of the light curve and significantly enhance the visibility of the main profile.

We can see that the analysis of the properties of outbursts in dwarf novae gives us the possibilities to investigate various phenomena. Even in a single system, the individual outbursts can display largely different profiles. Search for the common features is thus needed. Also a search for the relation between the outburst properties and the long-term activity of a given system is very important.

*2.4. Variations of the Outburst Recurrence Time in Dwarf Novae.* It is known that the recurrence time $T_C$ of outbursts in dwarf novae can vary by a large amount. However, analyses using the method of the O–C residuals from a trial period [22, 23] have shown that the variations of $T_C$ are not chaotic and that well-defined trends can be found in the O–C curves. The relation between the O–C curve and $T_C$ is as follows: a

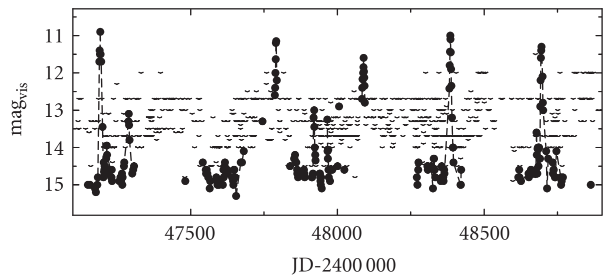



Figure 3: (a) Part of the light curve of the dwarf nova CH UMa showing the bright and faint outbursts (AFOEV data). Closed circles denote detections. Upper limits are marked by $\vee$. Adapted from [23].

linear profile of the O–C curve, no matter what its slope is, implies a constant $T_C$. A parabolic profile of the O–C curve implies a linear change of $T_C$ ($T_C$ is increasing/decreasing if the parabola is curved upward/downward). This method can work even if some outbursts are missing due to the gaps in the data, if the profile of the O–C curve is not too complicated. Monitoring is thus needed to avoid or at least diminish the gaps in the data.

Variations of $T_C$ in CH UMa can serve as an example. This system displays two types of outburst (bright and faint) (Figure 3). Evolution of the peak magnitude of these outbursts is displayed in Figure 4(a) while the accompanying O–C variations can be seen in Figure 4(b). The observed long-term trends in the O–C curves suggest that the individual outbursts depend on each other in a given system. $T_C$ shows large jumps and/or cyclic variations, but the precise profile of the O–C curve depends on the given system. The episodes or intervals of both increase and decrease of $T_C$ in a given dwarf nova are not explicable by the evolutionary processes in the system. Extensive analysis of the relation between $T_C$ and the outburst parameters is needed to find the physical mechanisms (e.g., variations of $\dot{m}$ or the disk viscosity) which control the activity of these systems.

*2.5. Supersoft X-Ray Sources.* As mentioned in Section 2.1, supersoft X-ray sources are a unique type of X-ray sources. They are usually close systems, with their orbital periods of the order of hours to a few days, in which the mass transfer onto a white dwarf occurs at a very high rate ($\dot{m} \approx 10^{-7}\,M_{\odot}\,\mathrm{yr}^{-1}$). This allows a steady-state hydrogen burning on the surface of the white dwarf [3]. This burning is the source of intense soft X-ray radiation, but its detectability depends on the interstellar extinction and metallicity of the source. The optical radiation originates mostly from the reprocessing off the X-rays in the disk and the donor star [24]. The known supersoft X-ray sources are mostly located in the Magellanic Clouds and in M31, because soft X-rays are easily absorbed in the interstellar medium in our Galaxy. In addition to these supersoft X-ray sources, there are several groups of objects that could be their close relatives. V Sge stars display very similar properties in the optical passband as the above mentioned supersoft X-ray sources. The potential members were listed by [25]. The work in [26] revealed

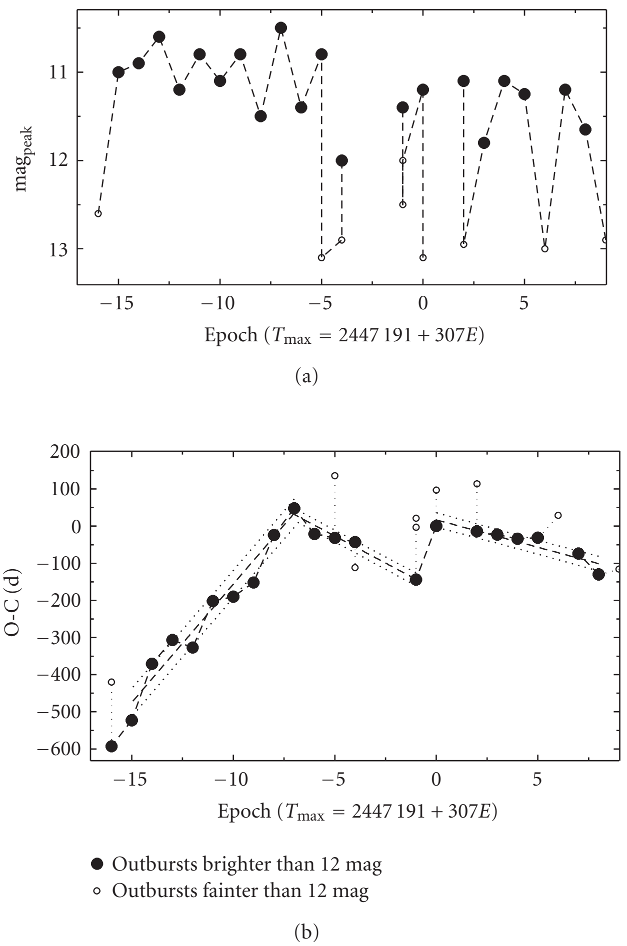



Figure 4: (a) Evolution of the peak magnitude of the outbursts in CH UMa. The bright and faint outbursts are marked by closed and open circles, respectively. (b) The O–C diagram (defined in Section 2.4) for the outbursts in CH UMa. The ephemeris is included in the title of the abscissa. The bright and faint outbursts are resolved. The O–C values of the faint outbursts are negative (positive) if they occurred before (after) the following (preceding) bright outburst. The faint outbursts are connected with the bright outburst, having the same epoch number, by a line for clarity. Adapted from [23].

that V Sge is a luminous, very soft X-ray source during the optical low state, turning into a faint hard source in the optical high state due to a variable amount of circumstellar matter. The optical changes are thus in antiphase with those in X-rays, in a similar way as in another supersoft X-ray source, RX J0513.9-6951 [27]. V Sge is a very active system; it displays a complicated long-term activity, whose character changed considerably during about 40 years (e.g., [28]). Some symbiotic systems can be supersoft X-ray sources, too (e.g., [29, 30]), They usually contain a white dwarf, accreting matter from its red giant companion via a strong stellar wind or Roche lobe overflow. They often display strong and complicated long-term activity, with the typical amplitude exceeding 1-2 mag. Some peculiar symbiotic novae may be related to supersoft X-ray sources, too.

*2.6. Polars.* Polars are CVs with a strongly magnetized white dwarf accretor (e.g., [1]). Streaming matter is threaded through the accretion column onto the magnetic pole(s) of the white dwarf because the strong magnetic field of the white dwarf prevents formation of the accretion disk. This transferring matter is usually the dominant source of radiation in the optical and X-ray spectral regions in the high state. Since the disk is missing, the variations of the mass transfer rate are rapidly reflected in the luminosity of the polar. The matter falling onto the white dwarf forms an accretion column above its surface. This column is a source of radiation via several mechanisms. Cyclotron emission is dominant in the optical and UV passbands, while the medium and hard X-ray emission is due to bremsstrahlung. Also soft X-ray excess, probably caused by the thermal emission from the surface of the white dwarf heated by the impact of matter, can be present (e.g., [1]). Some polars occasionally enter a low state (e.g., [31]) because of a transient reduction or cessation of the mass transfer. Only when the polar enters this low state, the light contribution of the donor and the white dwarf becomes significant. The X-ray luminosity fades substantially in this time period because neither the white dwarf nor the donor is strong X-ray emitters.

An example of the complicated relation between the optical and X-ray (1.5–12 keV) intensity in the individual high states of AM Her is displayed in Figure 5. Investigation of this relation enables us to relate the processes responsible for the emission in these spectral regions. AM Her is one of a very few CVs detected by ASM/*RXTE*. Nevertheless, the X-ray signal is weak, hence displaying a significant scatter. The data were therefore fitted by the code HEC13 (see Section 2.6 for details). It was found that the fits with $\epsilon = 1$, $\Delta T = 25$ d, and $\Delta T = 35$ d reproduce the main features of the light curve and significantly enhance the visibility of the main profile. This procedure also shows that the optical to X-ray intensity ratio differs considerably for the individual episodes of the high state (Figure 5(c)).

*2.7. Possibility to Detect and Identify Rare Phenomena in CVs.* Some intermediate polars, that is, CVs with a mildly magnetized white dwarf (e.g., [1]), were observed to display rare, peculiar brief flares with an amplitude larger than 1 magnitude. TV Col undergoes rare flares with an amplitude of about 2 mag. The duration of such an event is uncertain because of the gaps in the coverage, but it is likely to be shorter than one day (e.g., [32, 33]). The temperature of the inner disk region increased during this event [32]. Two flares, one of them represented by only a single point, were observed in V1062 Tau [34]. Also V1223 Sgr was observed to underwent two flares. The first one was sufficiently covered to show that it lasted only for several hours [35]. The second flare was found on a photographic plate (see below). The brevity of such flares makes their study very difficult. It is not known how frequent these flares can be because only a few such events have been observed in a given system due to fragmentary data. Monitoring of a large sample of systems can shed more light on the parameters of such events

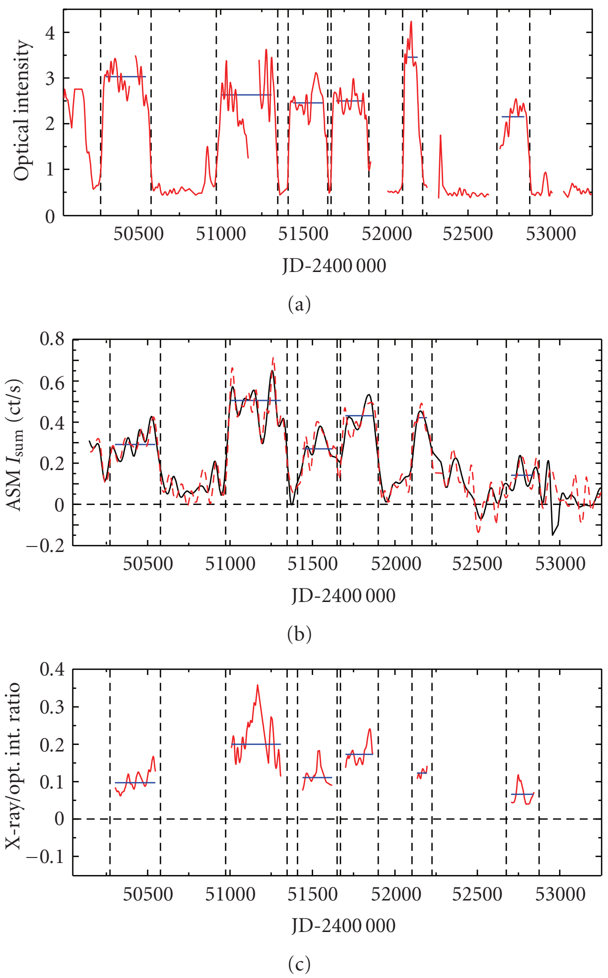



FIGURE 5: The light curve of the polar AM Her in the optical (a) (AFOEV data) and X-ray band (b) (ASM/*RXTE* data). The ratio of the X-ray to the optical intensity is shown in (c). Only HEC13 fits are shown. The dashed vertical lines denote the crossing of the level of 14.3 $\text{mag}_{\text{vis}}$. Solid horizontal lines denote the average intensity of the given high state. See Section 2.6 for details.

(amplitude, duration, recurrence time, variations of the color indices, relation of these events to the state of the long-term activity). Observing this sample can also help us reveal what system parameters are needed to give rise to such flares (orbital period, magnetic field, and spin period of the white dwarf . . . ).

Also investigation of the relation of the flares to the long-term activity is important. Between the flares, the $B$ magnitude of TV Col was at $\sim$14.5 mag($B$), without any fluctuations larger than several tenths of mag [33]. V1062 Tau displayed both high and low states and the observed flare occurred shortly after return to the high state [34]. V1223 Sgr represents an important example. Analysis of the Bamberg Observatory plates (one plate per night) (Figure 6(a)) clearly shows the importance of monitoring. Although the sampling of these data does not allow to determine the profile of the flare, the long-term coverage by the plates enables us to study the relation of the flare to the surrounding activity.

The statistical distribution of the brightness of V1223 Sgr is helpful in this case (Figure 6(b)). The marginally double-peaked distribution caused by the "common" variability of this system with the peak-to-peak amplitude of about 1.2 mag is clearly visible. It is defined by most measurements. Notice the sharp edge of this distribution at about 12.3 mag. The largely deviating point marked with an arrow represents the outburst in JD 2439 383. This point is not a simple continuation of the "common" variability. The outburst, albeit defined only by a single data point and representing thus only slightly more than 1 percent of the observations, significantly affects the skewness and excess of the statistical distribution. On the other hand, the mean magnitude and its standard deviation are affected by the outburst only marginally. These outbursts thus can be responsible for the "outliers" in the long-term light curve, although their profiles remain unresolved due to the sampling.

*2.8. Properties of the Outburst Light Curves in SXTs.* Since SXTs are often intense X-ray emitters during outbursts, these events are usually discovered by the X-ray monitors onboard the satellites. Nevertheless, the optical monitoring is important also in this case. The typical duration of the outburst is from several weeks to more than a month, while the recurrence time $T_C$ of outbursts is more than a year, although exceptions exist (e.g., [2]). A single observation per night may thus be sufficient to cover the profile of outburst, although denser coverage is desirable for the often steep rising branch. The rise of the optical emission to the peak magnitude may even be of the order of a day. In the case of GRO J1655-40, the 1996 outburst begun sooner in the optical passband than in X-rays [36]. It is important to note that the observed relation between the profile of the optical and X-ray light curve differs not only for the individual SXTs, but also for a single binary if more of its outbursts were observed. The issue of what comes first, that is, X-rays or optical emission, remains ambiguous. Simultaneous observations of a series of outbursts of Aql X-1/V1333 Aql in the optical and X-ray passbands by [37] revealed that the duration of the outburst in various passbands and the X-ray/optical intensity ratio differ substantially for the individual events. The optical versus soft X-ray correlation during a set of outbursts revealed that two kinds of outbursts exist in this system. In addition, Aql X-1 displayed a peculiar flare with the reddening of the $B$-$V$ index during its 1978 outburst [38]. Its nature is unclear. Since the duration of this flare was considerably shorter than the outburst itself, monitoring in various filters during the outburst is very important.

The conditions in the disk of SXTs, reflected in the light curves of the outbursts, are affected by the presence of a very hot inner disk region; it acts as irradiating source during outburst and is thought to modify the disk structure [39, 40]. Nevertheless, the observations show that the relation between the optical and X-ray flux, hence irradiation of the disk, is more complicated than thought previously [41]. The parameters of irradiation of the disk can be studied by analysis of the profile of the light curve of the outburst. In order to obtain a meaningful ensemble of outbursts,

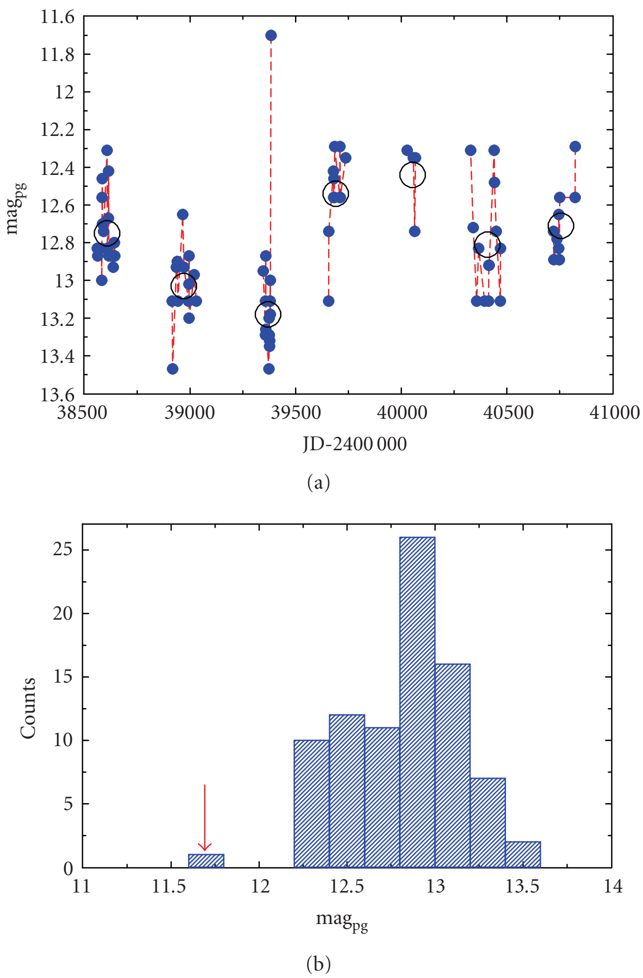



FIGURE 6: (a) Segment of the long-term light curve of the intermediate polar V1223 Sgr on the Bamberg photographic plates. The intervals of missing data are seasonal gaps. Closed circles represent the individual observations. The data in the densely covered segments are connected by a line to guide the eye though the complicated profile of the light curve. Large open circles denote the annular averages. The largely deviating point in JD 2439 383 represents a flare and is not included in the annular mean. (b) Statistical distribution of the brightness in the long-term light curve. The largely deviating point marked with an arrow represents the flare.

monitoring is necessary to obtain a sufficient number of the well-mapped outbursts in a given SXT. Also spectroscopic observations are important in this regard. Although it is difficult to arrange a spectroscopic monitoring of such relatively faint sources like SXTs, rapid communication of the outburst to the spectroscopists will be certainly helpful.

At least some SXTs display significant variations of their quiescent optical brightness. The long-term optical variations of GS 1354-64/BW Cir observed by [42] had the amplitude of about 1 mag. Since SXTs are very faint in quiescence (~20 mag($V$)), their optical monitoring is a difficult task. Dense series of the multifilter observations are needed to determine the profile of such variations (small outbursts, gradual waves?) and to resolve among the individual emission mechanisms (e.g., thermal or synchrotron).

*2.9. Variations of the Outburst Recurrence Time in SXTs.* The recurrence time $T_C$ of outbursts in SXTs in which a series of outbursts was observed varies by a large amount in a similar way as in dwarf novae [43] (Section 2.4). In some extreme cases, the mean $T_C$ of some SXTs can even be as short as those in dwarf novae with long orbital period (CH UMa, DX And, GK Per). The available observations suggest that the individual outbursts in a given system are dependent on each other. $T_C$ shows large jumps and/or cyclic variations, but the precise profile of the O–C curve depends on the given system. The episodes or intervals of both increase and decrease of $T_C$ in a given SXT are not explicable by the evolutionary processes. It emerges that the disk of SXT is not considerably depleted in outburst, but that a lot of matter remains (at least in some systems). A gradual accumulation and redistribution of matter in the outer disk region plays a large role in the observed activity.

*2.10. Optically Bright Persistent LMXBs.* Although studies of the long-term optical activity of persistent X-ray binary sources are rare, the available findings show strong and mostly unexplored activity.

HZ Her/Her X-1 is an LMXB with the orbital period of 1.7 days. It consists of a neutron star and a main sequence donor (e.g., [44]). The principal source of the optical variability is the changing aspect of the secondary's hemisphere, facing the neutron star and strongly heated by X-rays. The usual kind of the optical activity of HZ Her with the large orbital modulation (active state) is occasionally interrupted by the intervals of inactive states. In that time, the heating disappears and the system remains near the minimum brightness of the orbital modulation (e.g., [45]). All episodes of the inactive state were discovered only on archival plates and were shown to recur on a time scale of about 10 years in the first half of the 20th century [46], prior to the onset of the X-ray satellite era.

The long-term light curve of HZ Her composed of the photographic observations is displayed in Figure 7(a). Both the active state and two episodes of the low, inactive state were captured. The remarkably different profiles of the orbital modulation in both states can be seen in Figure 7(b). Notice the much smaller amplitude, appearance of the secondary minimum lagging behind phase 0.5, and the flat profile outside the primary and secondary minima. It can be seen that even one plate per night is enough to reveal the character of the activity in HZ Her.

Sco X-1 is an optically bright (~12.5–13.5 mag($V$)) and hence easily observable LMXB. Its long-term light curve in blue light made of measurements on archival photographic plates [48] displayed fluctuations by about 1 mag, with a trend of fading. This system is also significantly variable on short timescales, during a single night [49]. Its optical brightness is related to the complicated variations of the X-ray spectrum [50].

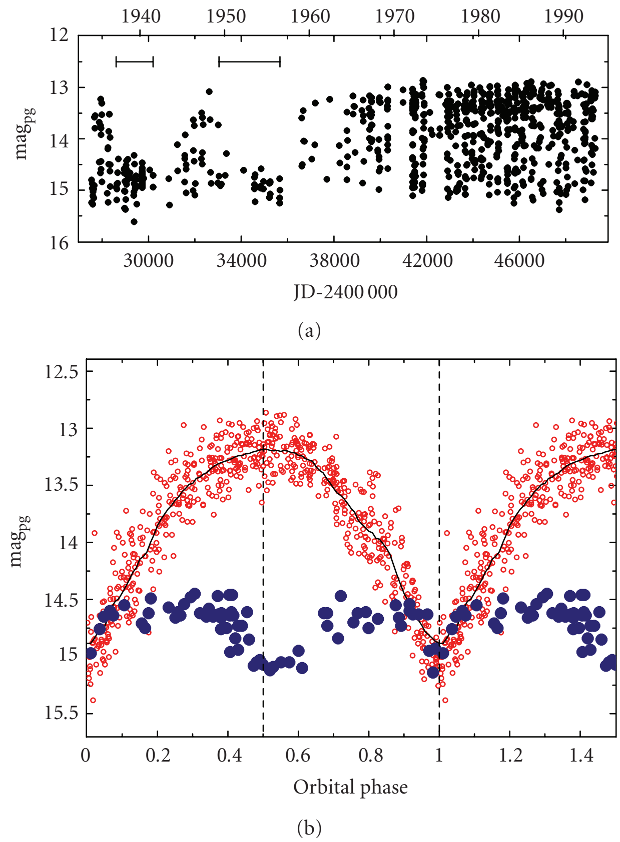



Figure 7: (a) The optical light curve of HZ Her/Her X-1, composed of 807 observations obtained with the D 40 cm and D 17 cm astrographs of the Sonneberg Observatory. The intervals of inactive states are marked by the horizontal bars. Adapted from [47]. (b) The orbital modulation of HZ Her. Open circles denote the extended active state between February 1959 and October 1993 [47]; the smooth line represents the moving averages of these data. Closed circles mark the orbital modulation in the low state observed by [45].

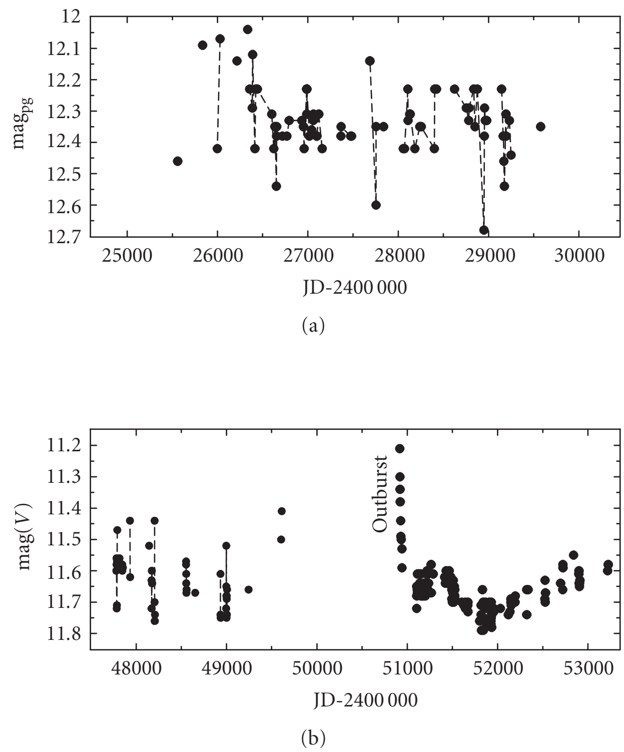



Figure 8: (a) Photometric history of the microquasar CI Cam according to the Bamberg photographic observations in the blue band (similar to the $B$ band) (1928–1939). Points are connected by a line in the densely covered segments. Typical uncertainty is 0.05 mag. (b) The activity in the $V$ passband in 1989–2004. The peak of the 1998 outburst is out of the scale. Adapted from [58, 60].

*2.11. Microquasars.* Microquasars are X-ray binaries with relativistic jets [51]. This category comprises both high- and low-mass systems [52], including some SXTs (e.g., GRO J1655-40 [53]) mentioned in Section 2.8. Here, we point the attention to two relatively bright, peculiar systems which displayed large-amplitude outbursts seen in the X-ray, optical, and radio bands. Relativistic jets were launched during these events.

CI Cam (XTE J0421+560) undervent an intense outburst in 1998. Its characteristics are quite atypical among X-ray transients (e.g., [54]). The X-ray outburst was accompanied by a strong brightening in the optical and radio. It can be explained by the thermal-viscous instability of the accretion disk, analogous to the outbursts of SXTs [55, 56]. This event influenced both the photometric and spectroscopic properties of the system (e.g., [57, 58]). The compact object is most likely a black hole or a neutron star [55, 59]. The photometric history during the years 1928–1939 and 1989–2004 is shown in Figure 8. Notice the difference in the activity before and after the outburst.

The postoutburst activity of CI Cam (1999–2004) displayed significant variations of the continuum, as suggested by the changes of the color indices. This activity was interpreted by [57, 58] as due to several superposed spectral components, with the division of their dominant contributions near $\lambda = 550$ nm: free-free emission from the wind and/or envelope in the red and near-IR, and a (pseudo)photospheric emission in the blue region. Hysteresis of the shifts in the color-color diagram can be ascribed to the H$\alpha$ changes which are not any simple variations of the combined continuum and weaker emission lines at stable H$\alpha$ emission. The H$\alpha$ region evolves on the timescale of hundreds of days [58].

Huge changes of the extinction in X-rays and no detectable extinction variations in the optical passband suggest that the X-ray emission comes from the close vicinity of the mass-accreting black hole (refilling of the disk after the outburst?), not from the giant donor [58].

We can thus see that this system is clearly active even in quiescence and especially the large change of the character of its activity after the outburst deserves further careful monitoring over a broad spectral range.

V4641 Sgr (SAX J1819.3-2525) represents another example of a microquasar (B9III donor and a black hole [61]) with a major outburst in September 1999, observed in X-rays, optical, and radio. Radio structures suggest superluminal jet ejection [62]. Several smaller peculiar outbursts with the multipeak structure followed the 1999 event. Their mean $T_C$ was 377 days, with a trend of a decrease (e.g., [63]). They were interpreted as cyclo-synchrotron emission associated with magnetic flares [64]. The preoutburst observations on the Bamberg photographic plates (1964–1967) reveal ongoing activity of the system. It displayed low-amplitude fluctuations on the timescale of several weeks, independent on the orbital phase [63].

*2.12. Optical Afterglows of GRBs and Their Color Indices.* The relativistic jet radiating the synchrotron emission is the dominant source of emission of GRB and its afterglow from gamma-ray to the optical, infrared, and radio spectral region [65]. While the duration of the gamma-ray emission is typically from less than a second to several minutes, optical afterglow lasts much longer (days). Optical emission can be therefore searched for even using untriggered observations. The intensity of the emission depends on the inclination angle of the jet with respect to the observer; the jet has to point almost exactly to the observer.

Deep observations are needed to detect optical afterglow in later phases after the gamma-ray trigger, since most of them are fainter than 18 mag($R$) at $t - T_0 \approx 1$ day, although some of them can be brighter than 14 mag($R$) in their early phase, at $t - T_0 \approx 0.01$ day [66]. The profile of the light curves suggests that most optical afterglows are the brightest immediately after gamma-ray trigger, and display a power-law decay later on. Many observed optical afterglows display striking similarities in both their time evolution and spectra (Figure 9—ensemble of optical afterglows [67, 68], optical afterglow of GRB 060218 [69–71]). Their absolute $R$ magnitudes $M_{R_0}$ were $k$-corrected according to [67] and corrected for the Galactic extinction according to [72]. The profiles of these curves are mutually similar although $M_{R_0}$ of the individual afterglows can differ by about 4 mag at a given time since the gamma-ray trigger in rest frame, $(t - T_0)_{\text{rest}}$.

spite of the scatter in magnitude, the individual events display remarkably similar color indices with negligible changes during the first several days, which is important for discriminating them from other kinds of objects. Photometric observations using the commonly available filters provide us with important information on the spectral profiles of optical afterglows. Color-color ($B$-$V$ versus $V$-$R$) diagram of optical afterglows from Figure 9 is displayed in Figure 10. It contains the color indices in the observer frame. Only observations within $t - T_0 < 10$ days were plotted. Multiple indices of the same optical afterglow are connected by lines for convenience. They were corrected for the Galactic reddening, so only reddening in the host galaxies of these GRBs could remain. Notice a very strong clustering of the color indices of most afterglows. The same clustering was also obtained for the $V$-$R$ versus $R$-$I$ diagram. This suggests that although these events possess a large range of redshifts $z$ (they are at $z < 3.5$), they display very similar spectra. Besides the astrophysical analysis, these specific color indices give us

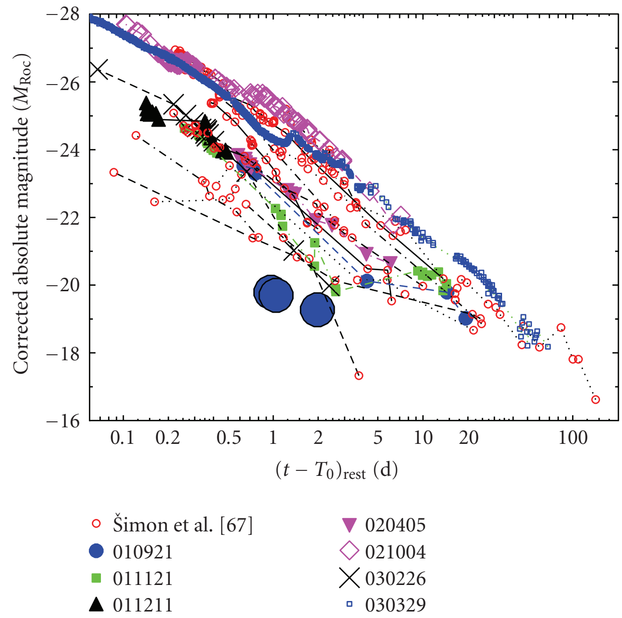



FIGURE 9: $k$-corrected absolute $R$ magnitudes of the ensemble of optical afterglows of long GRBs from [67, 68]. The magnitudes of the early phase of optical afterglow of GRB 060218 are plotted as large closed circles. Rest frame time interval $(t - T_0)_{\text{rest}}$ is used for the abscissa.

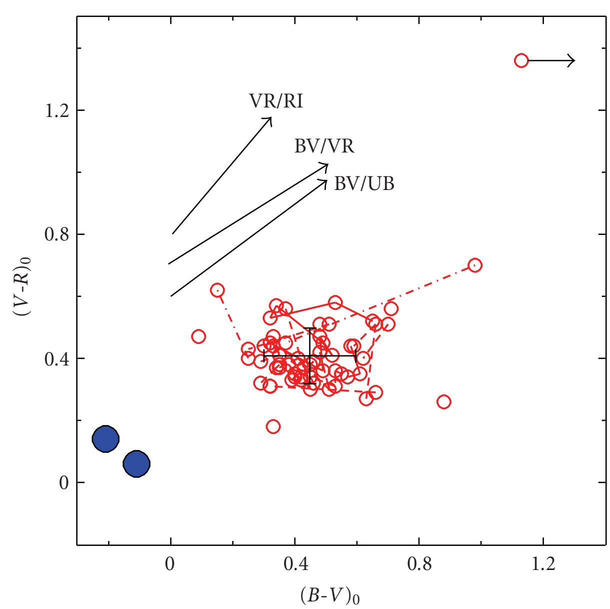



FIGURE 10: Color-color ($B$-$V$ versus $V$-$R$) diagram of optical afterglows of long GRBs. The color indices were corrected for the Galactic reddening. Multiple indices of the same optical afterglow are connected by lines for convenience. Optical afterglows of the ensemble [67, 68] are denoted by open red circles. The mean colors (centroid) of the whole ensemble, including the standard deviations, are marked by the large cross. The outlying optical afterglow of GRB 060218 (closed blue circles) is not included in the calculation of the centroid. The representative reddening paths for $E_{B\text{-}V} = 0.5$ are shown. Adapted from [67, 68], where a detailed information can be found.

a hope to resolve whether an optical transient event is related to a GRB even without available gamma-ray detection. Of course, a trivial case is that a GRB occurs outside the field of view of the gamma-ray telescopes of the operating satellites, so only optical transient can be detected by the observer on the Earth. Nevertheless, the missing gamma-ray emission can indicate the so-Called orphan afterglow. These events represent an important challenge for astrophysics. They can be caused by several mechanisms. Gamma-ray emission from many GRBs cannot be observed because the jet is not pointing to the observer, but the late-time afterglow is less beamed and can reach us [73]. Failed GRBs [74] are another possibility. According to [74], the number of failed GRBs may even be much larger than that of successful bursts and so there should be many orphan afterglows. Deep optical monitoring can decide between these possibilities. Multifilter observations are important to help discrimination between optical afterglows and other kinds of transients. Since these events are extragalactic, the magnitude of a given transient can be corrected for the reddening caused by the dust in our Galaxy according to [72]. Nevertheless, the extinction and reddening caused by the dust in our Galaxy are not serious if the parts of the sky far from the Galactic plane are monitored. The scatter of the color indices of the individual optical afterglows is therefore expected to be small even without such a correction.

## 3. Conclusions

We can see that the dense series of observations are necessary to investigate the properties of the long-term activity of the X-ray sources. Especially resolving the profiles of the state transitions, like the rising and decaying branches of outbursts, is important for our understanding of the relevant physical processes involved. It is also important to place these events in the context of the long-term activity of a given system. Only a long observing series can enable us to form a representative ensemble of events (e.g., outbursts) in (a) a given system, (b) in a type of systems. Of course, the exciting search for the unexpected and unique phenomena can be carried out only by monitoring. The optical monitoring is important for the investigation of the systems containing a compact object which, although the source of X-ray emission, may not be detected in X-rays due to the beaming and/or big intrinsic extinction.

We emphasize the very important role of the X-ray monitors like ASM onboard the *RXTE* satellite on our understanding of the processes operating in X-ray sources. We argue in favor of the development of more sensitive X-ray monitors that will be able to detect the long-term activity of CVs to enable analysis of the simultaneous behavior in the X-ray and optical passbands.

In addition, the current results of the analysis of the rare and/or unexpected phenomena show that unique transient brightenings also occur in systems which are relatively bright even in quiescence and hence easy to monitor. This means that observation of transient activity including large-amplitude outbursts can be carried out even with small aperture monitoring telescopes. The microquasars CI Cam and V4641 Sgr can serve as examples.

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