The importance of monitoring of X-ray sources in the optical passband

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Binary X-ray sources
Accretion disk

Compact object
(WD, NS, BH)

Stream impact onto disk

Mass

Donor, lobe-filling star

Cataclysmic variables (CVs), Low-mass X-ray binaries (LMXBs)

Dominant source of luminosity: accretion process

Donor, lobe-filling star

Stream impact onto disk

Accretion disk

Donor - thermal radiation (optical, IR)

Outer disk region - thermal radiation (UV, optical, IR)

Close vicinity of compact object - thermal radiation (X-rays)

Inner disk region – thermal radiation (far UV in CVs, soft X-rays in LMXBs)

CVs: brehmsstrahlung (X-rays)

LMXBs: Comptonizing cloud (inverse Compton process - hard X-rays)

Outer disk region - thermal radiation (UV, optical, IR)
Mechanisms for the long-term activity in CVs and X-ray binaries

- **Changes of mass transfer rate** $m$ **from donor onto compact object** (timescale: days, weeks, months, years)

- **Thermal instability of accretion disk** (timescale: days, weeks, months)

- **Hydrogen burning on white dwarf (in CVs)**:
  - **Episodic**:
    - *classical nova explosion* (timescale: weeks, months)
    - *recurrent novae* (timescale: weeks, months)
  - **Steady-state**:
    - *supersoft X-ray sources* (timescale: days, weeks, months)
Binary systems with outbursts:

Dwarf novae

Soft X-ray transients (SXTs)
Systematics of cataclysmic variables (CVs) and low-mass X-ray binaries (LMXBs)

**CVs – optical light curves**

<table>
<thead>
<tr>
<th>Star</th>
<th>Type</th>
<th>Outburst Type</th>
<th>JD - 2 400 000</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH UMa</td>
<td>dwarf nova</td>
<td>(U Gem-type)</td>
<td>48000 to 53000</td>
</tr>
<tr>
<td>AH Her</td>
<td>dwarf nova</td>
<td>(Z Cam-type)</td>
<td>50600 to 51100</td>
</tr>
<tr>
<td>V 751 Cyg</td>
<td>nova-like</td>
<td>(VY Scl-type)</td>
<td>46000 to 52000</td>
</tr>
</tbody>
</table>

**LMXBs – X-ray light curves**

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 1608-52</td>
<td>Transient source (SXT)</td>
</tr>
<tr>
<td>4U 1705-44</td>
<td>Persistent source</td>
</tr>
<tr>
<td>Ser X-1</td>
<td></td>
</tr>
</tbody>
</table>

**Increase of mass transfer rate**

**Thermally unstable disk** (most time)

**Change of long-term activity from large-amplitude, isolated outbursts starting from the baseline quiescent state to the dominant relatively small fluctuations in the high state.**

**Increasing time-averaged mass accretion rate** \( m \) \( (\text{also increasing}) \)
Problems in long-term coverage

- **X-ray binaries:** often bright in X-rays - easily observable by X-ray monitors, but often too faint in the optical (usually fainter than 16-18 mag except infrequent outbursts) - optical data are fragmentary or even absent.

- **Cataclysmic variables:** bright in the optical, so good long-term coverage is available, but X-ray data are fragmentary - too faint for X-ray monitors (with only very few exceptions).

- Transitions between activity states (e.g. outbursts, high/low) are often fast and unpredictable - monitors with wide field of view are needed to resolve them.
Decaying branch – the most stable part of outburst, slope independent of peak outburst luminosity

Properties of outburst light curves in dwarf novae – the case of DX And

Relation between peak magnitude of the outburst and the slope of its rising branch. The slope (rate of rise $\tau$) is expressed in days/mag.

Fainter outbursts have slower rise, hence they start closer to the WD.

Appearance of the well covered outbursts, shifted along the time axis to match the decaying branch of the template.

- Simon (2001)

Monitoring is necessary to obtain sufficient number of well-mapped outbursts in a given dwarf nova to determine a meaningful ensemble of outbursts
Cataclysmic variables – dwarf nova GK Per

Complicated relation between the optical and X-ray profile of outburst

Intermediate polar—very long $P_{\text{orb}}=1.99$ d (Crampton et al. 1986)

Exploded as classical nova in 1901

Fluctuations by $\sim$1 mag after return to quiescence, or they developed into infrequent dwarf nova outbursts (Sabbadin & Bianchini 1983, Hudec 1981)

One of very few CVs detected by ASM/RXTE

X-ray start of outburst can precede the optical start by up to 40 days (Binachini & Sabbadin 1985). Models even up to 80–120 days (Kim et al. 1992)
Cataclysmic variables – dwarf nova SS Cyg
Complicated relation between the optical and X-ray profile of outburst

Optical - accretion disk
X-ray - boundary layer

Large dependence of the outburst profile on the passband
Large structural changes of the emitting regions during outburst
Boundary layer changes from optically thin, geometrically thick to optically thick, geometrically thin during outburst

Wheatley et al. (2003)
Variations in quiescence between two outbursts (means)

Cataclysmic variables – outbursts of intermediate polar DO Dra

Rare outbursts caused by thermal instability of accretion disk embedding magnetized white dwarf

Profile of optical LC in accordance with X-rays

Simón (2000)

Szkody et al. (2002)

Simón (2003)
Outburst of V 1223 Sgr on Bamberg photographic plates
(one plate per night)

V1223 Sgr: "var"
Reference stars: "C1" and "C2"
North is at the top.

Rare flares in cataclysmic variables

V1223 Sgr

Intermediate polar (nova-like)

Statistical distribution for brightness can reveal rare, short brightenings even in sampled data

Sept 11, 1966, JD 2 439 380
Sept 14, 1966, JD 2 439 383

"Normal"

Moment of the peak

Flare (outburst)
Outburst of SXT in various passbands – the case of A0620–00 / V616 Mon

Influence of the inner disk region on the outburst rise in SXT – the case of GRO J1655–40

X-rays

Outburst begins sooner in the optical than in X-rays (filling of advection-dominated accretion flow (ADAF) by a hot, viscous disk)

Optical

Optic al (B & pg.)

X-ray

Radio

Charles & Coe (2006)

Hameury et al. (1997)
Relation between the evolution of the optical magnitude and X-ray flux (1.5-12 keV) during the 2000 outburst.
Long-term optical variations of SXT in quiescence – the case of GS 1354–64 / BW Cir

Episodes of anomalous color indices in outburst – the case of Aql X-1 / V1333 Aql

Episodic reddening of the B-V inxes – launch of synchrotron-emitting jet?

Casares et al. (2009)

Charles et al. (1980)
Properties of outburst light curves in SXTs – the case of Aql X-1

Multiwavelength long-term monitoring

(a) Near-IR $J$-band light curve
(Aql X-1 + contaminating star)

(b) Optical $R$-band light curve
(Aql X-1 + contaminating star)

(c) Logarithm of soft X-ray (1.5-12 keV) count rate (ASM/RXTE)

Simultaneous observations of the outburst in the optical and X-ray passbands – duration of the outburst in various passbands and X-ray/optical ratio may differ substantially – mass outflow from the inner disk region?

Monitoring is necessary to obtain sufficient number of well-mapped outbursts in a given SXT to determine a meaningful ensemble of outbursts
Optical vs. soft X-ray correlation during a set of outbursts

Monitoring is necessary to obtain sufficient number of well-mapped outbursts in a given SXT to determine a meaningful ensemble of outbursts
Variations of the outburst recurrence time in dwarf novae and SXTs

**Aql X-1 (SXT)**

Relation between O-C curve and $T_c$:
- Linear profile of O-C curve - constant $T$
- Parabolic profile of O-C curve - linear change of $T$

**CH UMa (dwarf nova)**

Peak intensity of outbursts in Aql X-1 (1.5-12 keV)
Profiles of outbursts - very large variety of profiles exists (even outbursts in a single system display largely different profiles). Search for the common features is needed.

Search for the relation between the outburst properties in the long-term activity of a given system.

Parameters of irradiation of disk (mainly in SXTs). Evolution of irradiating body during outburst.

Analysis of a possible shielding of outer disk region by a structure (mainly in SXTs).

Role and evolution of spiral arms that may appear in disk during outburst (observations versus models).
Variations of the recurrence time of outbursts, $T_c$, of SXTs are large, but not chaotic - long-term trends can be clearly resolved - individual outbursts depend on each other in a given SXT. This behavior of SXTs can be compared with that of dwarf novae determined from the optical data.

Behavior of $T_c$ in SXTs is quite similar to dwarf novae (e.g. Vogt 1980, Simon 2000, Simon 2002ab). Mean $T_c$ of some SXTs can be even as short as those in dwarf novae with long orbital period $P_{\text{orb}}$ (CH UMa, DX And, GK Per).

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 (dependent on the system). Episodes...
Low-mass X-ray binary HZ Her/Her X-1

Remarkably different profile of the orbital modulation with respect to the active state:
- Much smaller amplitude
- Appearance of secondary minimum
- Flat profile outside primary and secondary minima

Data folded with orbital period of 40.8 hours

Sonneberg photographic data (one plate per night)

Hudec & Wenzel (1976)
Long-lasting active state

Data folded with orbital period of 40.8 hours

Analysis of statistical properties of the folded data for various phases of the cycle of the disk precession

Data folded with orbital period 40.8 hours and smoothed for various phases of the cycle of the disk precession

Low-mass X-ray binary HZ Her/Her X-1

Sonneberg photographic data (one plate per night)

Simon et al. (2002)
Low-mass X-ray binaries – Sco X-1

Long-term light curve in blue light. Annular means determined from archival photographic plates.

Light variations are composed of the rapid and long-term activity.

Rapid brightness variations during a single night

X-ray spectral changes vs. $B$ band magnitude

Orbital variation from 150 nights in 1971–1973

Hudec (1981)

Moffett et al. (1973)

Augusteijn et al. (1992)

Augusteijn et al. (1992)
Supersoft X-ray sources
Supersoft X-ray sources

Unique type of X-ray sources

(Quasi)steady-state thermonuclear burning of accreted hydrogen on the surface of the white dwarf.

Intense soft X-ray emission is produced, but its detectability depends on the interstellar extinction and metallicity of the source.

Optical emission comes from both the reprocessing of X-rays in the disk and from the disk viscosity.

Specific clustering of color indices during active state
(Quasi)steady-state thermonuclear burning of accreted hydrogen on the white dwarf surface

Intense soft X-ray emission is produced, but its detectability depends on the interstellar extinction, temperature of white dwarf, and metallicity of the source (these are the causes of anticorrelation).

Optical changes in antiphase with X-rays


Greiner & van Teeseling (1998)
Comparison of visual and photoelectric (CCD) obs.:

**Visual data** make densely covered long-term light curves.

**Photoelectric data** are suitable for color variations and rapid changes (orbital modulation).

Supersoft X-ray sources – V Sge

Simon et al. (2001)
Rise from a low state

Supersoft X-ray sources – V Sge

- **U-B constant**
- **B-V decreases in the upper part of the transition**

Color – magnitude diagram

Simon et al. (2001)
Supersoft X-ray sources – V Sge

Long-term activity and orbital modulation

Simon et al. (2002)
Supersoft X-ray sources – RX J0513–69

Quasi)steady-state thermonuclear burning of accreted hydrogen on the surface of white dwarf. Intense soft X-ray emission is produced, but its detectability depends on the interstellar extinction, temperature of white dwarf, and metallicity of the source (these are the causes of anticorrelation).

Optical changes in antiphase with X-rays

Reinsch et al. (2000)

Unique type of X-ray sources

Cowley et al. (2002)
Cataclysmic variables – polar AM Her

Relation between the optical and X-ray light curve in the individual episodes of the high state. Only the HEC13 fits are shown.

Statistical distributions of the optical and X-ray intensity in the
Microquasars
Microquasars

X-ray binaries with relativistic jets

CI Cam = XTE J0421+560

Simon et al. (2007): reanalysis of data of Barsukova et al. (2002) using color indices

The outburst can be explained by the thermal instability of the accretion disk embedding the black hole, analogous to the outbursts of soft X-ray transients (Simon et al. 2006).

CI Cam reddens in outburst in spectral region longward of Balmer jump – very rare behavior among soft X-ray transients (SXTs) (a kind of X-ray binaries).

On the contrary, color indices of SXTs usually decrease during outburst.
Photometric history according to the photoelectric and CCD observations (years 1989 - 2004)

Peak of the 1998 outburst is out of scale. Notice the difference in the activity before and after the outburst.

CI Cam = XTE J0421+560

Photometric history according to the Bamberg photographic observations in the blue band (similar to the B band) (years 1928 - 1939)

Points are connected by line in densely covered segments. Typical uncertainty is 0.05 mag.

Simon et al. (2007)
UBVRI light curves and color changes in post-outburst interval (daily means) (1999 - 2004)

CI Cam = XTE J0421+560

Post-outburst activity

Labels 1, 2, 3, 4 - important moments in curves, used for orientation in color diagrams.

Simon et al. (2007)
Post-outburst activity (1999 - 2004):

- Significant variations of continuum; dominant line changes would lead to independent variations of indices. Not explicable by changes of reddening intrinsic to CI Cam.

Interpretation: several superposed spectral components. Division of dominant contributions of spectral components near $\lambda = 550$ nm: free-free emission from wind and/or envelope (in red and near-IR; Clark et al. 2000, A&A, 356, 50).

Hysteresis due to H\(\alpha\) changes

Brightness variations are NOT caused by extinction changes.

Decline from outburst

Post-outburst

CI Cam=XTE J0421+560

Simon et al. (2007)
CI Cam = XTE J0421+560

Optical vs. X-ray activity in quiescence

Dashed vertical lines - moments of X-ray observations.

(a) V band data in post-outburst interval

(b,c) Variations of EW of HeI 5876 (in Å) and Fell 6318 (data from Barsukova et al. 2002, AZh, 79, 309).


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

(e) H column density $N_H$
Recent photometric history of V4641 Sgr. Peak of the 1999 main outburst is near the left hand edge of the plot. Four smaller echo outbursts are marked by arrows. Each of them is defined by multiple observations. Examples of echo outbursts. Notice the multi-peak structure of outburst and the accumulation of the points near the peak mag. This implies that the outburst does not consist of a long series of short, narrow peaks starting from the quiescent level. Simon & Henden (2009).
Evolution of $T_c$. Dashed horizontal lines - length of the reference period of 377 d to show the relatively small scatter of $T_c$ of the echo outbursts. Two positions of the main outburst are shown: (1) - two missing echo outbursts; (2) - one missing echo outburst.
Statistical distribution of the brightness fluctuations in quiescence.

**S1**: Fluctuations in quiescence.

**S2**: The general level of brightness is higher than in S1, a weak outburst occurred from this level.

**S3**: The state similar to that in

Simon & Henden (2009)
Conclusions – CVs, X-ray binaries, microquasars

- Dense series of observations covering the intervals of several years are necessary to investigate the properties of the long-term activity:
  - resolve the state transitions, like rising and decaying branches of outbursts and high/low states.
  - put these events to the context of long-term activity of a given system
  - form the representative ensemble of events (e.g. outbursts) in (a) a given system, (b) in a type of systems

This is important for our understanding of the physical processes involved.

- We emphasize the very important role of X-ray monitors like ASM onboard RXTE on our understanding of the processes operating in X-ray sources.
Currently used methods to resolve the contribution of a supernova (SN) in optical afterglows (OAs):

(a) Spectroscopic - only for brighter OAs, large telescopes needed;

(b) Late bump in the light curve of OA - not a certain classification of SN, because also inhomogeneities in the circumburst medium can give rise to a bump (Eldridge et al. 2006, MNRAS, 367, 186).
Typical light curves of optical afterglows (OAs) of long GRBs

GRBs occur during core-collapse of a massive star or during a merge of compact objects. Relativistic jet is the dominant source of radiation from gamma-ray to the infrared (and radio) spectral region. Intensity of emission depends on the inclination angle (jet has to point to the observer).

Brightness of most OAs already falls when they are discovered in the optical passband. Typically, power-law decay is observed, but fluctuations may be superimposed on it. OA lasts much longer than GRB (days versus seconds or minutes).

Luminosity proportional to $t^{-a}$

All observations are in the $R$ band (red light) and their time is in the observer frame.

Zhang et al. (2006)
Light curve of the OA of GRB030329 according to the data of Fynbo et al. (2004). Data in the dashed boxes are the ones used for the determination of the color indices. The data are connected by the lines for convenience.

Error bars are included, but they are usually smaller than the symbols.

well observed light curve of the OA GRB030329 whole R band curve to show the evolution of the brightness.

for filters - only those (often averaged) points which were used for calculating the color indices.
Ensemble of OAs of long GRBs ($0.17<z<3.5$; $t-T_0<10$ d) in the observer frame, corrected for the Galactic reddening. Multiple indices of the same OA are connected by lines for convenience. The mean colors (centroid) of the whole ensemble of OAs (except for GRB000131 and SN 1998bw) are marked by the large cross.
$B-V$ vs. $V-R$ diagram of OAs ($t-T_0<10.2$ d). The colors are corrected for the Galactic reddening. Multiple indices of the same OA are connected by lines for convenience. The mean colors of the whole ensemble (except for GRB000131) are marked by the large cross. The colors of SN1998bw are shown only for comparison.

**BV data:**
- UVOT

**R band data:**

Representative reddening paths are for $E_{B-V}=0.5$ mag.

**Color-color diagram for the early OA of GRB060218**

- Simon et al. (2009)
Time evolution of the color indices of the OA of GRB030329 (solid circles):

- Horizontal solid line with error bars
- mean color
  indices of ensemble of 25 OAs (Šimon et al. 2004).

- Synthetic colors of SN 1998bw, SN 2002ap and the group of Type Ic supernovae (database and code of Poznanski et al. 2002), with the passbands and
Data were corrected for the reddening and light contribution of the host galaxy.

Data were interpolated to determine the color indices. Separation of the colors appropriate to the early OA and SN 2006aj is clear for $UVW2-B$, $UVW1-U$, $UVM2 - UVW1$. 

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**B band light curve**

- $\text{(B-V)}_0$
- $\text{(UVW2-UVW1)}_0$
- $\text{(U-B)}_0$
- $\text{(UVW2-UVM2)}_0$
- $\text{(UVW1-U)}_0$
- $\text{(UVW2-B)}_0$

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**Color indices**

Simon et al. (2009)
The horizontal lines in the figures represent the mean color indices of an ensemble of 25 observed afterglows of long GRBs (Simon et al. 2004, AIPC, 727, 487). These are independent on redshift.

Synthetic colors of several types of supernovae (Poznanski et al. 2002, PASP, 114, 833) are calculated for redshift $z=0.03$ of GRB060218.

- Large open circles: UVOT data of SN 2006aj
- Large closed circles: ground-based data of SN 2006aj

Simon et al. (2007, 2009)
Skewness of the histogram -0.17 suggests asymmetric distribution with a tail toward fainter mag – many supernovae can have the initial optical flare similar to the optical afterglow of GRB – observations in various filters in the early phase of the supernova are needed. The observing angle (with respect to the jet axis) may play a role in the observability of the early emission.

Statistical distribution of abs. $R$ magnitudes of OAs of long GRBs at $(t-T_0)_{\text{rest}} = 1.5 \text{ d}$. Both the $k$-corrected and uncorrected values are displayed. Mag of all the OAs was already decreasing.

Histogram of absolute magnitudes of OAs: the early OA of GRB060218

Simon et al. (2009)
Magnetars
Light curve in the individual passbands for $t-T_0 < 7$ d ($T_0$ is the time of GRB070610).

Time evolution of the scatter of the points in the light curve.

Comparison of the profile of the $I$ band light curve in three epochs after $T_0$.

Flares become more narrow with the progress of the outburst.

Castro-Tirado et al. (2008, 2009)
Simon et al. (2009)
Dense series of the VRI observations (dur. ~65 min) (June 11, 2007). The I and R data are not quite simultaneous. Significant fluctuations of the brightness are apparent (~1 mag, timescale ~15 min).

**Comparison of (R-I) of J1955 with the ensemble of OAs of long GBs from Simon et al. (2004), plotted as a function of redshift z (only OAs with z < 3.5, t-T₀ < 10.2 d).** Color index of each OA is dereddened for the Galactic extinction and is in the observer frame. Linear fit and 1σ deviation of the ensemble are displayed. Color index of J1955 is displayed for three E.

Optical emission in SWIFT J1955 is due to synchrotron radiation.
General conclusions

Dense series of observations are necessary to investigate the properties of the long-term activity:

- resolve the state transitions, like rising and decaying branches of outbursts and high/low states.
- place these events in the context of long-term activity of a given system
- form a representative ensemble of events (e.g. outbursts) in (a) a given system, (b) in a type of systems

This is important for our understanding of the physical processes involved.

Search for the unexpected and unique phenomena

Wide-field optical monitoring is important for a search for and investigation of
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