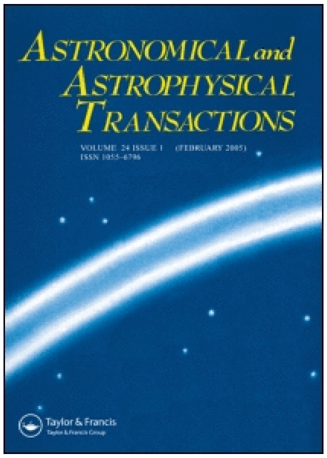

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Session 5 : Stars and Stellar System

PHOTOMETRIC INVESTIGATIONS OF LOW-MASS X-RAY BINARIES WITH HIGH TIME RESOLUTION

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We present the results of a search for ultrafast optical variability among 11 low-mass X-ray binaries (LMXBs). Observations have been carried out with the hard- and soft-ware photometrical complex MANIA (Multichannel Analysis of Nanosecond Intensity Alterations) with the 6-m telescope of SAO RAS and 2.15-m telescope of CASLEO, Argentina, with 10^{-7} s time resolution. Eight of them showed no short-time variability on the time-scale from 10^{-7} to 40 s.

Five extremely short flares of 0.5–5 ms duration, 0.1–1 ms rise times and very high amplitudes (> 40) have been detected from A0620–00. Lower limits for the brightness temperature in the zones of flare generation are 10^9–10^{11} K.

Two flares of about 0.25 s duration have been recorded from the X-ray burster MXB1735-44; the brightness of the object has increased 15–30 times during these flares. These flashes show fine structure on time-scales of about 5–6 ms (confidence level > 95%). Brightness temperatures for different phases of the above flashes ranged from 5×10^7 K to 10^{10} K.

Stochastic variability was detected from GRO J0422+32 in a wide range of time-scales, from 5×10^{-3} to 10^2 s, simultaneously in different pairs of bands (U B, B V, B R). The power spectrum of the variations is practically flat. The shortest flashes with rise times of about 5–40 ms have brightness temperature higher than 10^8 K, for an estimate of the distance to the object of 2.4 kpc.

All detected events with high probability can be caused only by non-thermal processes. These results are apparently evidence that there are some departures from the standard model of hydrodynamical accretion on to compact objects.

KEY WORDS LMXBs, optical variability, observations, ultrafast flares, non-termal processes

1 INTRODUCTION

The present investigations are part of a high time resolution research programme in astrophysics. The main goal is to study the possible very fast optical variability of astrophysical objects on a time-scale from 10^{-7} to 10^{2} s (Shvartsman, 1977; Beskin *et al.*, 1982). One of the aims is to examine radiation from accreted or ejected plasma around compact objects of solar masses – white dwarfs, neutron stars, black holes (single and companions of binaries). The environments of such objects are promising laboratories to search for very rapid events: the geometrical extent can be very small, the energy density very high, the magnetic fields enormous. MANIA experiment has been carried out to search for and investigate these astrophysical phenomena in the Special Astrophysical Observatory since 1977. A special photometrical complex, registration system, software was created. This allows one to observe different astrophysical objects with a time resolution up to 10^{-7} s (Beskin *et al.*, 1982; Plokhotnichenko, 1983; Zhuravkov *et al.*, 1994). The 6-m telescope has been used in the observations since 1978. High-speed photometer and MANIA hard/software were mounted on the 2.15-m telescope of the Observatory Leonsito (CASLEO) in Argentina in 1991 as well.

Here we report some of our results of the study of very short optical events (irregular and periodic) from X-ray binaries A0620-00, GRO J0422+32 and MXB 1735-44.

In spite of the great progress in the study of X-ray binary systems in recent years, mary problems still remain to be solved in this field. In particular, the final choice between two models of accretion on to a compact object in a binary system-hydrodynamical and magnetoflaring (Shakura and Sunyaev, 1973; Pustil'nik and Shvartsman, 1974; Galeev *et al.*, 1979; Ikhsanov and Pustil'nik, 1994) – has not been made. Photometric observations with high time resolution (up to 10^{-7} s) are a powerful tool to investigate some peculiarities of X-ray objects in the optical range, their structure and the actual physics of the process of accretion on to compact objects.

Within the hydrodynamical model scenario, the bulk of the optical radiation originates either in the relatively cool regions of the accretion disk (scale-length $> 100r_g$, where r_g is the Shwarzshild radius), or alternatively in the re-emission of X-ray photons in the outer regions of the disk, or the surface of a normal companion star. In the first case, the characteristic time-scale of optical flux variations must be greater than $t_v \approx 100r_g/c \approx 10^{-6}$–$10^{-3}$ s, while in the second case this time-scale should be in the order of $R_0/c \approx R_s/c \approx$ 1–100 s even if the X-ray flares are very short (where R_0 is the outer radius of the accretion disk and R_s is the radius of the normal star). It should be emphasized that, irrespective of the type of optical variation (stochastic, periodic or quasi-periodic) or their characteristic time-scales, the energy release mechanism in the standard accretion model is a thermal process. In other words, the brightness temperature of the flaring regions cannot exceed 10^7–10^8 K (Lipunov, 1987).

On the other hand, in the magnetoflaring model, the optical radiation is generated independently on the X-ray one by dissipation of magnetic fields and by the interaction of electrons with these fields near blobs of accretion structure (Pustil'nik, 1975; Beskin and Minarini, 1994). These processes can produce non-thermal optical flares (brightness temperatures $> 10^8$–10^9 K) on time-scales of 10^{-6}–10^{-2} s.

Low mass X-ray binaries (LMXBs), i. e. compact objects with a normal star companion (as a rule F–M spectral class dwarfs, Bradt and McClintock, 1983), are the most adequate systems for studying the accretion processes in the optical range because in such systems the normal component is faint enough to allow us to observe the optical radiation of the accreting plasma. In fact, for LMXBs, $L_x/L_{\rm opt} = 10$–10^4 and thus, the bulk of the radiation of a system is due to the accretion process. Also, LMXBs often display UV-excesses and emission lines of H, He, C IV, N III with typical double-peak profiles, connected with the accretion structure (Bradt and McClintock, 1983). It is important to point out that LMXBs are claimed to be the origin of different types of X-ray sources: X-ray novae, bursters, transients, stable objects (of Sco X-1 type). In any case, from the point of view of photometric observations with high time resolution, all these systems are interesting.

2 DETECTION OF NON-THERMAL OPTICAL FLARES OF LOW-MASS X-RAY BINARIES

Eleven LMXBs have been observed with MANIA (Multichannel Analysis of Nanoseconds Intensity Alteration) complex – five (X0041+33, A0620-00, X1728-169, X1813-14, X1957+11) of them in 1986 at the 6-m telescope of SAO (Shvartsman *et al.*, 1989), and six (2S0921-630, 4U1543-475, 4U1636-536, 4U1559-487, MXB1735-44, 4U1822-371) in 1991 at the 2.15-m telescope of CASLEO (Beskin *et al.*, 1994). We present an observation log of these objects in the Table 1.

Nova Per 1992 (GRO J0422+32) was observed in 1992–1994 with the 6-m and 1-m telescopes at the Special Astrophysical Observatory (SAO) of the Russian Academy of Science and with the 1.5-m telescope at the Bologna Astronomical Observatory (Italy). These systems are different kinds of objects; A0620-00 is an X-ray nova with the mass of a compact component more than $3M_\odot$, X1728-169 and X1957+11 have UV excesses and emission lines, MXB1735-44 is a burster of type II, GX339-4 is a strongly variable object ($\Delta m \approx 5$) with 20 ms flashes, etc.

Computer analysis of the data by these techniques has shown the absence of any brightness variations on a time-scale of 10^{-7}–10 s for all objects with the exception of A0620-00, MXB 1735-44 and GRO J0422+32. The upper limits for relative power of variable radiation components were 70–1.5%, respectively.

A0620-00. The 5 ms flashes were detected on February 13, 1986 (Figure 1).

The first two flares had durations of 3 and 5 ms and their rising times were 1–2 ms. The other three events lasted 0.4–0.5 ms with rising times of about 0.1 ms. We present parameters of the flares in Table 2.

The lower limit of the flare amplitude is 40 counts per ms and corresponding brightness temperatures are 5×10^9 K for first two and 5×10^{11} K for the others.

Table 1. Observation log of X-ray binaries with the MANIA-complex with the 6-m and 2.15-m telescopes

Object	*Date(UT)*	*Time(UT)*	m_V	*Telescope*
X0041+33	4.09.86	00:43-01:53	19.2	6-m
A0620-00	13.02.86	20:30-20:39	18.2	6-m
		21:13-21:18		6-m
	14.02.86	20:14-20:16	18.2	6-m
		20:23-20:27		6-m
		21:56-21:58		6-m
		22:08-22:17		6-m
2S0921-630	6.05.91	01:42-02:26	-	2.15-m
	7.05.91	02:46-04:07	15.8	2.15-m
4U1543-475	5.05.91	05:26-06:16	14.8	2.15-m
4U1636-536	7.05.91	05:27-05:43	17.2	2.15-m
4U1559-487	6.05.91	03:28-04:23	17.4	2.15-m
X1728-169	5.08.86	19:00-19:03	16.6	6-m
MXB1735-44	9.05.91	05:03-05:57	17.2	2.15-m
X1813-14	7.08.86	22:18-22:24	17.5	6-m
4U1822-371	5.05.91	07:15-08:01	15.6	2.15-m
X1957+11	6.08.86	19:31-19:55	19.3	6-m
		19:59-20:12	19.3	6-m

Table 2. Parameters of the flares of A0620-00

Flare Parameters	*1, 2*		*3, 4, 5*	
	Phase		*Phase*	
	Front edge	*All*	*Front edge*	*All*
t (ms)	1	3–5	0.1	0.5
Amplitude	40		40	
T_b (K)	5×10^9		5×10^{11}	

MXB 1735-44. Two flares with durations of about 0.25 s were detected (Figure 2). In order to study the fine structure of these events the detailed light curve, $I(t)$, was analysed by the splash method (Beskin *et al.*, 1994). First, the light curve of the flares was constructed using a time resolution $t = 5$ ms, as shown in Figure 2*a*. From this figure it is clear that the registered variation consists of two flares with a total duration of about 0.25 s and a rise time of about 0.10–0.12 s.

This primary light curve, $I(t)$, was smoothed with a rectangular time window. The full width being five times the time resolution, t. This smoothed curve, $\langle I(t)\rangle$, is shown in Figure 2*b*, where it is possible to see that the front edges of both flares have very steep gradients, lasting about 0.05–0.06 s.

This curve was used to construct so-called normalized discrepancies:

$$\delta I(t) = \frac{\Delta I(t)}{D[\Delta I(t)]^{1/2}}, \tag{1}$$

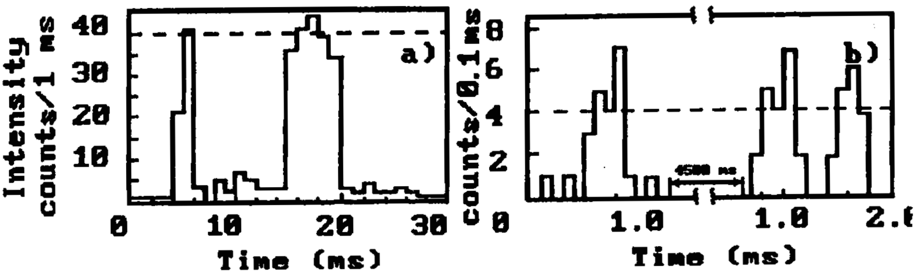

Figure 1 The ultrashort flares of A0620-00 on February 13, 1986, aperture is 4.3 arcsec, seeing is 1.5 arcsec, in white light (dashed line marks a level of maximal intensity corresponding to the limiting transfer rate into the computer PDP-11).

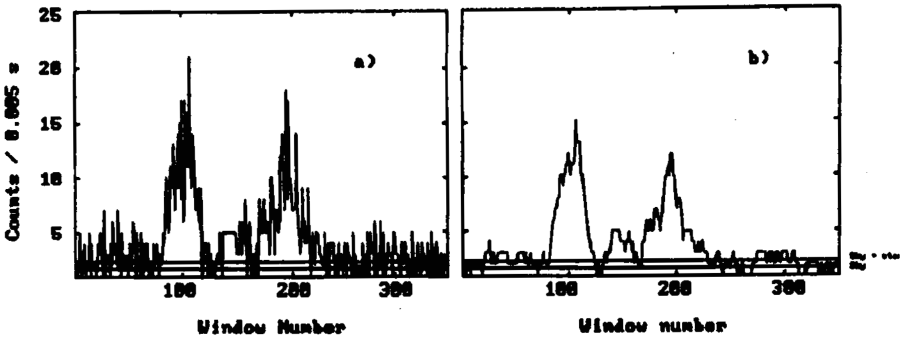

Figure 2 The light curves (aperture of 12 arcsec in white light) of two flares of MXB1735-44. *a*, Initial light curve; *b*, smoothed light curve.

where $\Delta I(t) = I(t) - \langle I(t) \rangle$ is the difference between the original and the smoothed brightness curve, and $D[\Delta I(t)]$ is the dispersion of this discrepancy calculated under the assumption that the data are due to a Poissonian process of variable intensity. When calculating $D[\Delta I(t)]$ we took in to account that $I(t)$ and $\langle I(t) \rangle$ are correlated. If there is no fine time structure, then $\delta I(t)$ must be close to a normal distribution with zero mean and unit dispersion. This was checked by the standard χ^2-test, and it was found that the hypothesis of a normal distribution must be rejected (at a confidence probability of 95–99.5%). In other words, both flares have a fine structure on time-scales of 5–10 ms (see Figure 2*a*). We present parameters of the flares in Table 3.

To check these results, we modelled flares close to the observed ones in shape, amplitude and normal noise. Their dispersions were assumed as proportional to the intensity at each time. The use of the procedure of fine structure search on these modelled events has revealed the absence of normalized discrepancy deviation from the normal distribution (confidence probability $> 90\%$). On the other hand, the search for fine structure on the background of smooth variations in the models represents the good sensitivity of this method (for example, for an filling factor

Table 3. Parameters of the flares of MXB 1735-44

Flare Parameters	*1*			*2*		
	Phase			*Phase*		
	Front edge	*Steep part of front edge*	*Fine structure*	*Front edge*	*Steep part of front edge*	*Fine structure*
t (ms)	110	60	6	120	60	5
Amplitude	32	26	26	17	17	17
T_b (K)	7.5×10^7	2×10^8	2×10^{10}	3.5×10^7	1.5×10^8	2×10^{10}

of 0.1 and signal-to-noise ratio of ≈ 2 the confidence probability at finding such structure is $> 95\%$). It must be emphasized that during all the observations with high time resolution either with the 6-m telescope or with the 2.15-m telescope, no object or reference star observed displayed a time behaviour similar to that of flares of A0620-00 and MXB 1735-44. Possible instrumental effects may be ruled out as they should have completely different characteristics (essentially shorter time-scales, regularity, etc.).

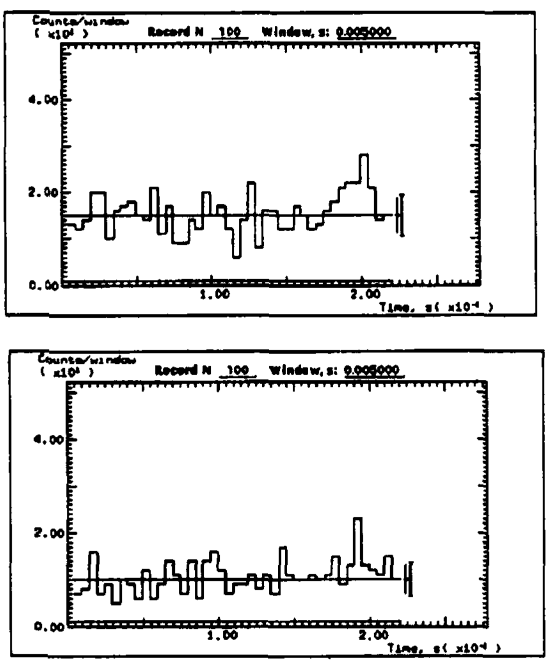

Figure 3 Flash of Nova Per 1992 with rise times 5–20 ms in V (bottom) and B (top) bands, January 18, 1993.

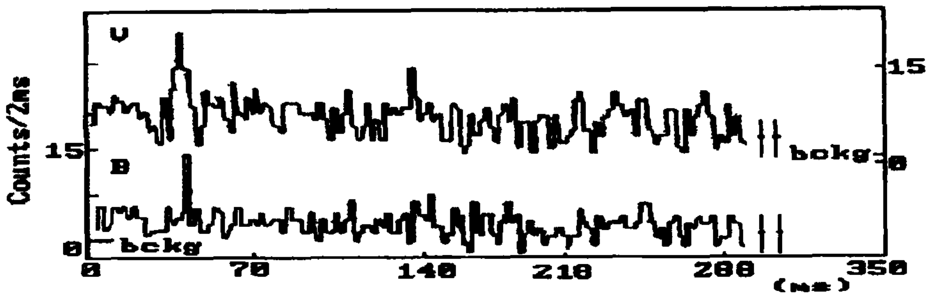

Figure 4 Flash Nova Per 1992 with rise time 4 ms, January 18, 1993.

A special analysis, in which the data of Schaefer *et al.* (1987) on the probability of satellite or meteorite records were used, shows that a nearby origin of the detected flashes is practically excluded (Shvartsman *et al.*, 1989; Beskin *et al.*, 1994).

GRO J0422+32. The object was more blue at the beginning of September, 1992 than in January, 1993. *UBVR* photometry shows flux and colour variations on a time-scale of minutes to hours with an amplitude of 10–20% (Vikul'ev *et al.*, 1991; Bartolini *et al.*, 1994). In high optical state the luminosity of Nova Per 1992 was irregularly variable in different colour bands on a time-scale from 4 ms to 200 s with amplitudes of 0.5–4 (see Figures 3 and 4).

The power spectrum of the detected variability was flat in the whole range of frequences from 0.01 to 250 Hz. As an example in Figure 5 we present a spectrum of Nova Per in the low-frequency range.

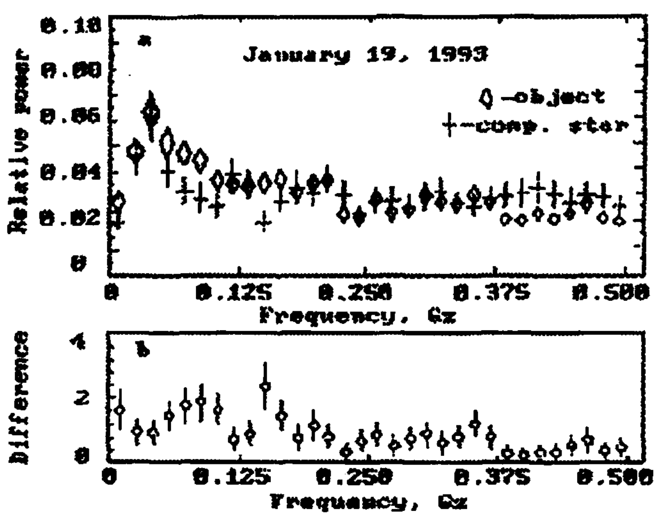

Figure 5 Part of the power spectrum of Nova Per 1992 optical variability. *a*, Normalized power spectra of the object and standard; *b*, relative difference between unnormalized spectra of the object and standard.

On the time-scales from 100 ns to 1 ms it is highly probable that variability was absent. During the low optical state ($V > 15^{m}.5$) Nova Per did not show any significant variability on the time-scale from 100 ns to 10^{-2} s.

The shortest flares had rise times of 4–40 ms (Figure 4) which allowed us to establish an upper limit of 10^8–10^9 cm on the size of the flares origin regions.

3 CONCLUSIONS

For all the detected events the low limits of the brightness temperatures were estimated by the formula:

$$T_b = 10^8 \rho_m t^{-2} f^{-2} D^2, \quad (2)$$

where t is the rising time in ms, f is the average frequency of observation (10^{15} Hz is assumed as unit), D is the distance in kpc and ρ_m is the flux in mJy. For calculation of T_b we took for A0620-00: $D \sim 1$ kpc, $B \sim 19^{m}.3$, $A_v \sim 1^{m}.2$; for MXB 1735-44: $D \sim 7$ kpc, $B \sim 17^{m}.2$, $A_v \sim 0^{m}.8$; for Nova Per: $D \sim 2.4$ kpc (according to Shrader *et al.*, 1992), $B \sim 13^{m}.9$, $A_v \sim 1^{m}.2$. We took into account the relation between the intensities of objects and backgrounds and the effective observation frequencies.

Thus, the brigthness temperatures for different flare regions of A0620-00 and MXB 1735-44 were higher than 10^8–10^{11} K and of Nova Per 1992 10^8–10^9 K. It is important to mention that for A0620-00 and MXB 1735-44 the detected events took place rarely, but they were common for GRO J0422+32. This may possibly be due to these objects being observed in different states: in a quiet shate with a low accretion rate for A0620-00 and MXB 1735-44 and in an active phase with a high accretion rate for GRO J0422+32.

All detected shortest events with high probability have a non-thermal origin since for T_b exceeding 10^8–10^{11} K it is very difficult to propose a thermal mechanism for photon generation. If we use a thermal mechanism to explain these events then X-ray luminosities would be very high ($> 10^{39}$–10^{40} erg s^{-1}) which contradict the X-ray data being obtained almost simultaneously with the optical observations.

It seems very possible that the generation of non-thermal optical flares cannot be explained by the hydrodynamical accretion model. In these cases the mechanisms discussed in the magnetoflaring accretion model might take place (Pustil'nik and Shvartsman, 1974; Ikhsanov and Pustil'nik, 1994).

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