Bull. Spec. Astrophys. Obs., 1998, 44, 43–49

Investigation of relativistic and fast variable objects with high time resolution

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Received January 4, 1998; accepted January 16, 1998.

Abstract. We describe the equipment and methods of search for and study of variable objects with a time resolution of 10^{-7} s in MANIA (Multichannel Analysis of Nanosecond Intensity Alterations) experiment. The MANIA hardware consists of a multicolour photometer, a specialized "time-code" converter "Quantochron 3-16" capable of measuring the moments of photon registration with an accuracy of 20 ns, a computer and a device for data storage. The MANIA software allows investigation of variability in a wide time range: on time scales smaller than the mean duration of intervals between acquired photons (10^{-7} – 10^{-3} s) statistical analysis of the interval distribution is performed; "classical" light curves are created on a time scale of 10^{-3} – 10^{2} s, which are investigated afterwards by different methods, such as power spectra analysis, variance analysis, etc.

The most significant results of the investigation of fast variability in the frames of the experiment are presented. Based on the results of search for ultrafast brightness variations of 40 objects, which are black hole candidates, the fraction of single black holes relative to the density of usual stars near the Sun has been estimated to be $5 \cdot 10^{-4}$. Studies of the fine time structure of 100 flares of UV Ceti stars have shown that the flares are of thermal nature. When investigating the Crab pulsar it has been found that the colour of its optical emission has varied with the phase of the period. The pulsed optical emission of the PSR 0656+14 on a level of 25^m has been registered for the first time. The study of the X-ray nova A0620-00 and GRO J0422+32 and the X-ray burster MXB1735-44 shows that these objects have revealed flares with duration of 1 ms – 100 ms. At least, the shortest flares are of non-thermal nature that contradicts the standard model of accretion onto the compact object in binary systems.

Key words: fast photometry, varibility, black holes, flare stars, pulsars, X-ray binaries

1. Introduction

The experiment MANIA (Multichannel Analysis of Nanosecond Intensity Alterations), the deep programme of search for and investigation of variability of different astrophysical objects on time scales from 10^{-7} s to 10^{2} s, has been carried out in the Special Astrophysical Observatory of RAS since 1972.

Brightness variations of such a type are caused by unstable processes of energy transformation in strong gravitational and/or magnetic fields of black holes and neutron stars (both single and components of binary systems), white dwarfs, active regions of flare stars. Observations of these objects with a high time resolution allow some conclusions to be drawn on both their physical properties and laws of interaction with accreting plasma. Photometry with the 10^{-7} s time resolution is the main method of the study. At present observations are carried out in several colour bands (the U, B, V, R bands) simultaneously (while before 1992 in one band only) with the help of a photometer, a "time-code" converter "Quantochron" and PC AT 486. The equipment allows to register arrival times of individual photons with an accuracy of 20 ns. Different mathematical methods are used afterwards to analyse the time series.

It is worthwhile to emphasize that the basic principles of the experiment were stated by V.F. Shvartsman (1977), it was under his guidance that the equipment complex was created and algorithms of search for variability were developed (Shvartsman & Tsarevskij, 1977; Mansurov & Shvartsman, 1977; Demchuk et al., 1977). After the death of V.F. Shvartsman investigations in the frames of the MANIA experiment have been continued by his colleagues.

Some similar programmes have been announced lately, (Dravins, 1994), but they haven't yield new astrophysical results yet.

2. MANIA complex description

In order to study a fast temporal variability a special photometrical hard/software complex was created which consists of a photometer, a registration system "Quantochron 3-16" – a special "time-code" converter encoding arrival times of each detected photon (Zhuravkov et al., 1994) and a special data acquisition and reduction software (Plokhotnichenko, 1983, 1992).

The main characteristics of the "time-code" converter "Quantochron":

- the rate of data acquisition with the PC AT 286-486 is up to 370000 photocounts/s (in monochannel mode up to 750000 photocounts/s);
- photon fluxes are registered in 2^{16} channels (spatial, spectral, polarizational) simultaneously;
- the accuracy of timing is ±20 ns, the dead time is 20 ns; the equipment is supported with external synchronization by a precision standard time service.

Any device capable of registration of individual photons can be used as a detector. Usually observations are carried out with the 2-channel photometer, which is mounted at the N1 focus of the 6 m telescope (Vikul'ev et al., 1991). Its dead time is 10^{-7} s, therefore the dead time of the MANIA complex is 10^{-7} s as well. 4-channel photometer can be mounted at the prime focus of the 6 m telescope. Installation and testing of a 2-head 6-channel computer-controlled photometer with a CCD-guide are being carried out now.

3. Methods of data analysis

3.1. y_2-, d_2-function methods

When studying the superfast variability of faint objects on time scales up to 1 μs the classical methods for light curve analysis are not optimal. Thus, when observing a star of 18^m at the 6 m telescope (the intensity is about 10^3 photocounts/s), among 10^3 empty bins there will be on average only one bin with photocounts (of 1 μs duration). To increase the efficiency of data analysis, special, the so-called y_2-, d_2-function methods, were worked out (Shvartsman, 1977).

The y_2-function method is intended for variability analysis on a time scale smaller than the mean interval between photocounts. It is based on statistical analysis of time intervals between photons.

The y_2-function is defined as:

$$y_2(\tau_i, \tau_{i+1}) = \frac{P_o(\tau_i, \tau_{i+1})}{P_s(\tau_i, \tau_{i+1})} - 1,$$

where $P_o(\tau_i)$ is the fraction of intervals between photocounts with duration from τ_i to $\tau_{i+1} = 2\tau_i$ in the flux from the object; $P_s(\tau_i)$ is the same one for the standard flux (standard star or Poisson source).

The d_2-function method, which is an analog of the method of variances, is used to search for and investigate the variability on times larger than the mean interval between photocounts.

The d_2-function is defined as:

$$d_2(\tau_i) = \frac{D_o(n_o(\tau_i)) - D_s(n_s(\tau_i))}{[M(n_o(\tau_i))]^2},$$

where $D_o(n_o(\tau_i))$ and $D_s(n_s(\tau_i))$ are the sample variances of the number of photocounts $n_o(\tau_i)$ and $n_s(\tau_i)$ in the window of duration τ_i for the object and standard, respectively, and $M(n_o(\tau_i))$ is the expected value of $n_o(\tau_i)$. The algorithms and programmes of data analysis using y_2-, d_2-function methods are described in papers of Plokhotnichenko (1983, 1992).

3.2. Methods of search for periodical variability

3.2.1. Search for period

A special method of search for periodical variations of brightness (which is similar to the principle of Fresnel lense), the so-called "Fresnel lense-like" method, has been developed (Plokhotnichenko, 1992). The main idea of this method is as follows: long time series of recorded quanta are divided into small portions. Each of them is folded with a chosen "test" period to create a series of phased light curves, meanwhile, none of the light curves may show pulsed emission. All these light curves should be summed to obtain well-shaped profiles. But due to the difference between the test and the actual periods, the pulses will be out of phase, and as a result they will be widened or even vanish in the summed light curve. To avoid this, we sum up the obtained light curves taking all possible phase shift values corresponding to a great number of close periods. Then by means of statistical methods, we find the light curve with the most significant pulse profile (profiles). The corresponding test period value, this curve has been folded with, is the closest to the actual one.

It should be noted that when creating the resultant light curves with respect to mutual phase shifts with different test periods one can also take into account the phase shifts caused by time derivatives of the period if they can be defined from any considerations (the proper period evolution or the Earth rotation).

3.2.2. Period fine fitting

The method of period fine fitting is based on the iterative creation of series of light curves using data portions of short duration obtained at close moments of time with "test" values of the period and its derivatives (P, $\dot{P}$, $\ddot{P}$, etc.) and their further redetermination. As the calculated period parameters differ from the actual ones, the phase shifts of pulses for individual light curves occur. Having obtained the shift values one can derive more accurate values of the period parameters. We calculate the sum of squared differences of each couple of light curves as a function of their mutual shift. It will be minimum in the case the light curves are close in phase. To decrease the influence of noise fluctuations of the sums of squared differences near minimum, they are approximated by the least squares method. Then the minimum is searched for by analytic differentiation. The procedure of fine fitting cycles until the limiting, statistically defined, accuracy is obtained. The pulsar light curves folded at the best values of the period parameters P, $\dot{P}$, $\ddot{P}$ are used to search for fine structure of pulsar optical emission and to investigate its photometric features, colour variations, for example (Komarova et al., 1996).

3.3. Methods of light curve analysis

To study variability in a wide time range by the classical methods (light curves, fast Fourier transform and correlation analysis) a special software system for data reduction has been created. It is run under the X-Window for the Linux (Unix) systems on the basis of the XView library. It allows the following:

- analysis of quanta fluxes of the object under investigation and of the standard, obtained with MANIA complex in several colour bands simultaneously;
- creation of light curves on a given time scale and desired degree of detailing;
- investigation of light curves using power spectra, averaged over the chosen data amount;
- normalization of the power spectra of the object under investigation by the power spectra of the standard;
- calculation of statistical characteristics of the power spectra (variances, means);
- to transform the obtained data to the MIDAS format for further analysis.

The algorithms for power spectrum calculations described by Jenkins and Watts (1969) have been used. The data are processed in the interactive mode.

4. Search for black holes of solar masses

More than 25 years ago it was shown by V.F. Shvartsman (1971) that around an isolated black hole of solar mass a luminous halo of accreting gas is to be originated. The halo spectrum is lineless, the main energy is released in the optical range.

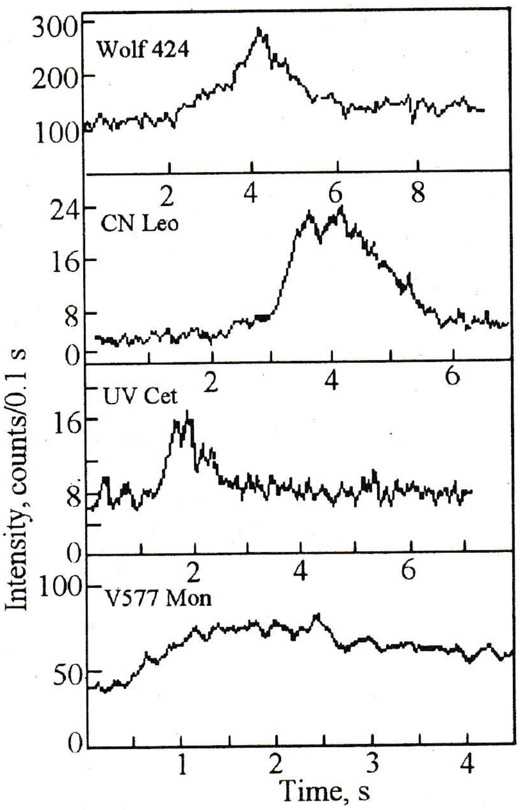

Figure 1: *Light curves of UV Ceti type stars with duration of front edges less than 1 s*

The intensity of radiation of plasma accreting onto the black hole is to vary with characteristic times $\tau \sim r_g/c \sim 10^{-5}$ s. This feature is the criterion for identifying any object with a black hole.

About 200 objects with continuous spectra have been chosen. Part of them are close to the Sun ($<$ 200 pc) – these are DC-dwarfs with large proper motions. Other objects, which are black hole candidates, are ROCOSes – star-like radio objects with continuous optical spectra.

20 DC-dwarfs and 20 ROCOSes were investigated in 1980–1987. No cases of variability on time scales of $10^{-6} - 10^{2}\,s$ were revealed (Shvartsman et al., 1989a, 1989b).

The absence of black holes among the 20 DC-dwarfs observed allows us to obtain the upper limit on the fraction of black holes relative to the density of normal stars near the Sun – $5 \cdot 10^{-4}$. This estimation is close to the fraction of stars with masses exceeding $30 M_{\odot}$.

5. Investigations of UV Ceti - type flare stars

In 1983–1986 a few observational runs of the red dwarfs UC Ceti, CN Leo, Wolf 424, V577 Mon were

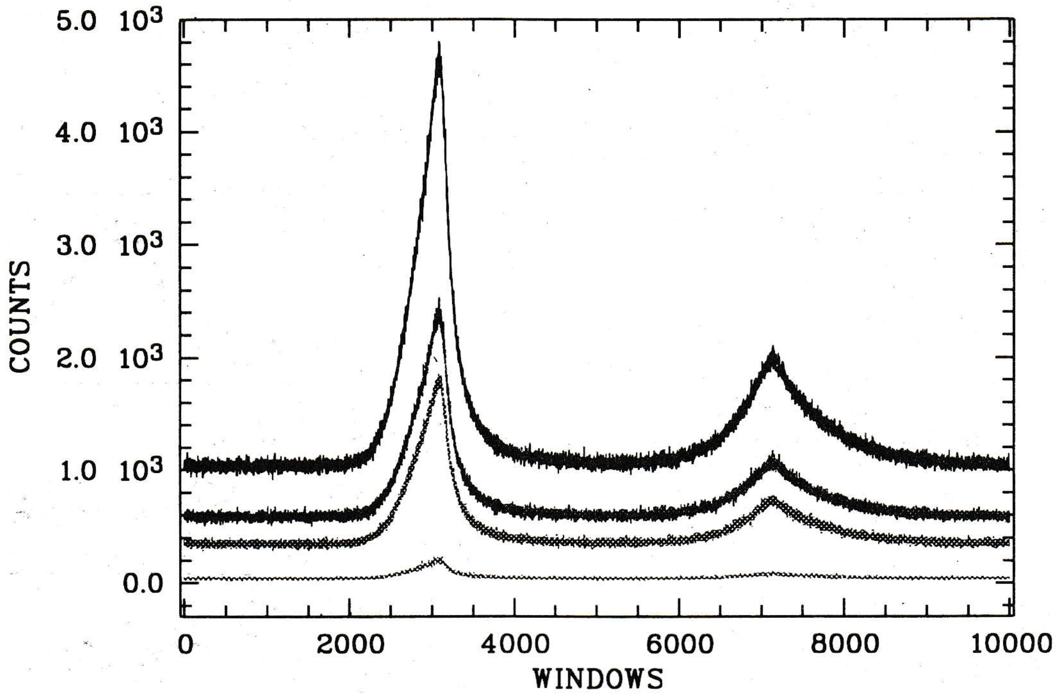

Figure 2: *The light curves of the pulsar PSR 0532+21 with a time resolution of 3.3μs in bands U+B+V+R, B, R, U (top to bottom).*

conducted. A total of more than 100 flares were detected with a $5 \cdot 10^{-7}$s time resolution, with amplitudes exceeding $0\overset{\rm m}{.}2$. According to the statistical analysis of the total information, 90 % of the flares had the front edges with durations less than 10 s, in four cases the brightness was increasing for 0.3–0.8 s (Fig. 1), the duration of the light curve features in their maxima and their intensity decreasing is certainly more than 0.5 s, no fine time structure was found for all the flares on times of $10^{-6} - 10^{-1}$s (Beskin et al., 1988). The minimum durations of the flare front edges are in good agreement with the estimates obtained within the thermal gaseous-dynamical model (Shvartsman et al., 1988a). All our results speak in favour of our knowledge the red dwarf flares to be of thermal nature.

6. Investigation of pulsars

6.1. The Crab nebula pulsar

One of the objectives of the MANIA experiment is the search for and investigation of pulsars. The first results of the Crab pulsar observations were published in 1983 (Beskin et al., 1983). After the development of the methods of determining the topocentric parameters of the pulsar rotation (P, $\dot{P}$, $\ddot{P}$) from the observed moments of quanta arrival, we obtained the pulsar light curve in the R band with a 3.3 μs time resolution. The analysis of its shape showed that the main pulse peak was flattened and its width was 230 μs at a level of 0.95 of the maximum value. We also estimated the limits to the fine time structure of the pulsar main pulse. Its amplitude was no more than 10 % on the time scale of 3.3 μs (Shvartsman et al., 1988b). In 1994 we obtained new observational data of the pulsar in the UBVR bands simultaneously. The light curves are shown in Figure 2.

Our analysis of the photometric data has shown the following: the fine time structure of the pulses is absent on times from 3.3 μs to 50 μs (intensity modulations are of statistical origin); the top of the main pulse is a plateau with a duration not more than 50 μs (Fig. 3); the interpulse space intensity is ≤ 1 % of the maximum brightness. To find possible variations of physical characteristics of the pulsar optical emission over the period, we studied its colours in different intervals of the light curve phases. The (U-B), (B-V) and (V-R) colour indices were quite constant within the limits of their accuracy at a level of $0\overset{\rm m}{.}05 - 0\overset{\rm m}{.}01$. The colour index (B-R), which was obtained with a maximum accuracy of $0\overset{\rm m}{.}003$ increased ("reddened") in the phase intervals related to the front wing of the main pulse and the tracking wing of the subpulse by 0.02 and 0.06, respectively (Komarova et al., 1996). This result should be interpreted theoretically, but it is possible to say even now, that there will be some difficulties in its explanation in the frames of the standard model, where it is considered that optical emission is generated near the light cylinder.

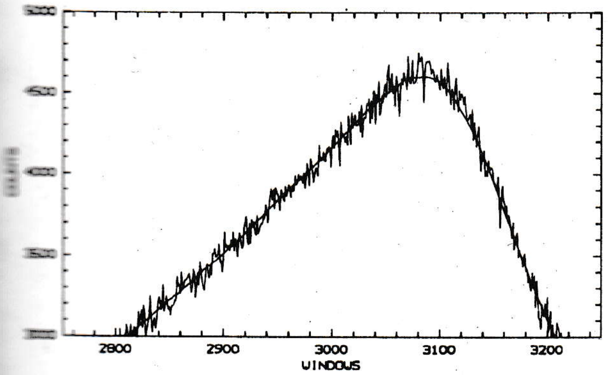

Figure 3: *The top of the peak of the main pulse with a time resolution of 3.3μs.*

6.2 Search for optical emission of radio pulsars

The first known millisecond pulsar PSR 1937+21 with a period of 1.56 s and the component of the binary system PSR 1953+29 with a period of 6.1 s have been investigated. A few million photons have been detected from each of them.

A search for periods based on pre-calculated values of topocentric periods has been carried out with the use of the special programme, described above. About 500 values of the "test"-period have been used. None of the cases of data convolution has shown any significant deviation from the Poisson scattering. Thus, the brightness of both optical pulsars does not exceed $26\overset{m}{.}5 - 27^m$ in the B band (Shvartsman et al., 1989c).

In cooperation with scientists from the Galway University College (Ireland) for the first time at the 6 m telescope a search for pulsed optical emission from radiopulsars with a panoramic photometer of high temporal resolution (Redfern et al., 1993) was carried out in December, 1995 — January, 1996.

We observed the radio, X-ray and γ-pulsar PSR 0656+14 and found optical pulsations in the B wavelength band ($B = 25\overset{m}{.}1 \pm 0.3$) (Shearer et al., 1997), the period of which is 0.385 s, which is close to the periods in the other ranges. The significance of the result is 0.01 %. The light curve shows a peak in phase with γ-ray data, and with a lag of 0.2 s from the peak of the radio signal.

7 Investigation of low-mass X-ray binary systems

Appearance of plasma accreting onto the relativistic component is the most essential for the objects of this type ("influence" of the normal companion is small). We have been observing about 10 such systems since [illegible] at the BTA and at the 2.15 m telescope of the CASLEO Observatory (Argentine) and continue the investigation. The most significant results have been obtained for two X-ray novae — A0620-00 (Nova Mon 1975) and GRO J0422+32 (nova Per 1992) (Shvartsman et al., 1989c; Bartolini et al., 1994) and the X-ray burster MXB1735-44 (Beskin et al., 1994).

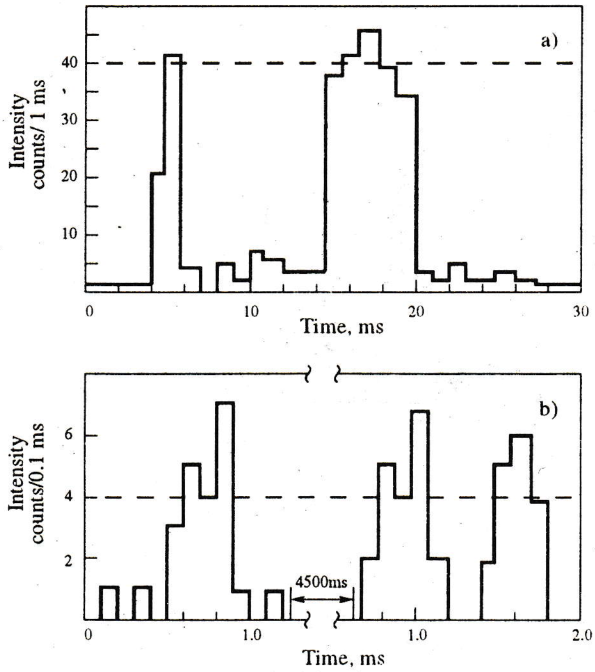

Figure 4: *Ultrafast flashes of A0620-00*

The first object has revealed few flares of 0.5 - 5 μs duration with 0.1 -1 μs front edges (Fig. 4). Given a distance to A0620-00 of about 1 kpc and a brightness of about 18^m, one can easily obtain the lower limit of the brightness temperatures in the regions of generation of flares, which is about $10^8 - 10^{10}$ K. This means that the observed flares are of nonthermal nature. Gro J0422+32 was observed in different stages - from 14^m near its maximum and to 18^m near the minimum - for 2 years (1992 - 1993). The intensity of the object in its high state ($< 15.5^m$) varies on times of $10^{-2} - 10^2$ s with amplitudes of $1 - 2^m$. Note that the brightness fluctuations are of stochastic character — there are no regular components. The brightness temperatures corresponding to the shortest flares exceed 10^8 K (for a distance more than 2 kpc), therefore, these events are probably connected with nonthermal processes. MXB1735-44 has also shown supershort flares with a duration of about 0.25 s and front edges of 0.10–0.12 s (Fig. 5). A fine structure on time scales of 5–10 ms has been found for both flares. Brightness temperatures in the regions of generation of such events are to exceed 10^8 K - 10^{11} K, which is evidence of their non-thermal nature. The flares detected can be explained by deviations from the standard model of accretion onto the com

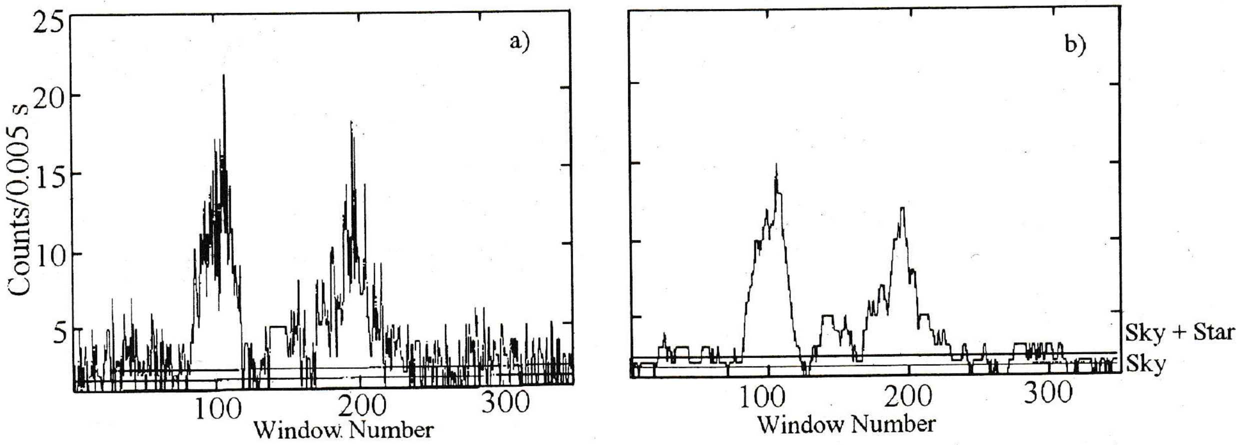

Figure 5: *Light curves of MXB1735-44: (a) - initial; (b) - smoothed.*

pact object in such close binaries. Thus, the results of the observations of A0620-00, GRO J0422+32 and MXB1735-44 are evidence in some cases of some deviations from the classical disk model. Moreover, probably, we observe just a fragmentary accretion structure of GRO J0422+32.

8. Prospects

Prospects of investigation of astrophysical objects with a high time resolution are closely connected with the creation of new-class detectors — coordinate-sensitive detectors (CSD) with a high spatial (50 μm) and time resolution (1 μs). The use of such systems will allow us to improve detection levels of fast brightness fluctuations of $2-3^m$. In other words, we will be able to find optical pulsars of $27-28^m$ and to look for black holes among $20-21^m$ objects. It seems to be very important to use CSD for spectroscopy of high temporal resolution. In this way we can investigate variations of temporal features of optical flares (both stochastic and periodic) which are re-emitted from the X-ray range by accretion structures in close binary systems. As these features are defined by spatial distribution of plasma inhomogeneity, it is possible to study their parameters and dynamics.

Next we will search for black holes in high density regions of interstellar gas, search for pulsed emission from radiopulsars and in young supernova remnants in nearby galaxies, carry out observations of the Crab pulsar and optical flares of X-ray bursters in several bands simultaneously and investigate optical transients connected with $\gamma-$bursters.

Acknowledgements. This work was partially supported by the Scientific and Educational Center "Cosmion", Russian Ministry of Science, Russian Foundation of Basic Research (grant 95-02-03691), Federal Programme "Astronomy" and ESO (grant A-02-023).

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