Sample of Cataclysmic Variables from 400d X-ray Survey

R. A. Burenin*1, M. G. Revnivtsev1, A. Yu. Tkachenko1, V. S. Vorobyev1, A. N. Semena1, A. V. Meshcheryakov1, S. N. Dodonov2, M. V. Eselevitch3, M. N. Pavlinsky1

1Space Research Institute RAS (IKI), Moscow, Russia
2Special Astrophysical Observatory RAS, Nizhnij Arkhyz, Russia
3Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia

Received November 24, 2015

Abstract — We present a sample of cataclysmic variables (CVs) identified among the X-ray sources from the 400 square degree X-ray survey based on ROSAT pointing data (400d). The procedure of the CV selection among the X-ray sources using additional optical and infrared data from Sloan Digital Sky Survey and WISE survey is described. The results of the optical observations of the selected objects carried out mainly with the Russian–Turkish 1.5-m telescope (RTT-150) and the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (BTA) are presented. Some observations have also been performed with the Sayan Observatory 1.6-m AZT-33IK telescope. Currently we selected eight CVs, four of which were found for the first time in our work. Based on this sample, we have obtained preliminary constraints on the CV X-ray luminosity function in the solar neighborhood in the low luminosity range, \( L_X \sim 10^{29}–10^{30} \text{erg s}^{-1} (0.5–2 \text{keV}) \). We show that the logarithmic slope of the CV X-ray luminosity function in this luminosity range is less steep than at \( L_X > 10^{31} \text{erg s}^{-1} \). From our CV X-ray luminosity function estimates it follows that few thousand CVs will be detected in the Spectrum-Röntgen-Gamma (SRG) observatory all-sky X-ray survey at high Galactic latitudes, which will allow to obtain much more accurate measurements of CV X-ray luminosity function in the luminosity range \( L_X < 10^{30}–10^{31} \text{erg s}^{-1} \).

Key words: cataclysmic variables, X-ray surveys, luminosity function

INTRODUCTION

Studies of samples of binary systems with accreting white dwarfs (cataclysmic variables, CVs) provide important information on physical processes in these systems that are difficult or even impossible to investigate by other means. For example, it turns out that the main mechanism of angular momentum losses for CVs with periods shorter than 2–3 h is the emission of gravitational waves [Faulkner, 1971; Paczynski 1981]. This prediction is confirmed by characteristic features in the properties of the CV population, such as the minimum in the distribution of orbital periods, \( P_{\text{min}} \approx 80 \text{ min} \) [Gänsicke et al., 2009], which agree well with the improved theoretical estimates of this quantity for the case of angular momentum losses through gravitational radiation in binary system [Knigge et al., 2011].

Nevertheless, there are also some discrepancies between observations and theoretical views. For example, theoretical modeling of the CV population shows that most of them must be in a state with a low accretion luminosity, and their companions must be degenerate objects (the so-called “post-bounce” CVs, e.g., Kolb 1993, Howell et al., 2001, Knigge et al., 2011). However, only a small number of possible post-bounce CV candidates are known to date [see, e.g., Littlefair et al., 2008, Aviles et al., 2010]. Among the problems that can be solved using studies of the statistically complete samples of CVs, there is a question of how and at what rate the masses of the white dwarfs (WDs) in these systems grow (e.g., Zorotovic et al., 2011). Since accreting white dwarfs are apparently the progenitors of type Ia supernovae, all such questions appear to be closely related to the studies of the properties of type Ia supernovae, which are used as “standard candles” for cosmological measurements.

It is also turns out that CVs contribute significantly to the Galactic ridge X-ray emission [Revnivtsev et al., 2009] and to the total X-ray luminosity of the Galaxy and other galaxies after the subtraction of the contribution from low-mass X-ray binaries [Sazonov et al., 2006, Revnivtsev et al., 2008a]. To obtain more accurate measurements of the contribution from the CV population to the total X-ray luminosity of galaxies, the studies of the statistically complete samples of these objects and the data that allow to measure the
X-ray luminosity function are also required.

The selection of the statistically complete CV samples in X-rays is one of the most natural approaches to obtain unbiased CV samples, because the X-ray emission is generated in the accretion flow near the WD surface and, therefore, is a property of all types of CVs (for a more detailed discussion, see below). Such samples can be obtained in various X-ray sky surveys. The X-ray luminosity functions of CVs were measured earlier using the data from the RXTE all-sky survey (Sazonov et al., 2006) and the ROSAT North Ecliptic Pole survey (Pretorius et al., 2007b; Pretorius and Knigge, 2012) as well as in harder X-ray band, using INTEGRAL (Revnivtsev et al., 2008b) and Swift (Pretorius and Mukai, 2014) data.

Almost all the objects detected in these surveys have X-ray luminosities \( L_X > 10^{30} \text{ erg s}^{-1} \). Since the CV X-ray luminosity function increases toward lower luminosities, the measurements of the CV number density at luminosities \( L_X < 10^{30} \text{ erg s}^{-1} \) should allow to refine the contribution from the CV population to the total X-ray luminosity of the Galaxy. In addition, at those low luminosities, one could expect to detect the large number of post-bounce CVs. Thus, the CV X-ray luminosity function measurements at low X-ray luminosities \( L_X < 10^{30} \text{ erg s}^{-1} \) are of great interest. To obtain these measurements one should use deeper X-ray surveys, with flux limits \( \sim 10^{-15} - 10^{-14} \text{ erg s}^{-1} \text{cm}^{-2} \). In this work for these purposes we used the 400 square degree (400d) X-ray survey, based on ROSAT pointing data, which were used earlier to detect galaxy clusters (Burenin et al., 2007). More than 37 000 point X-ray sources with fluxes above \( 10^{-14} \text{ erg s}^{-1} \text{cm}^{-2} \) were detected in this survey; about 22 000 of these sources were detected in the ROSAT fields overlapped with Sloan Digital Sky Survey (Burenin et al., 2016b). The optical observations with the aim to search the CVs among the X-ray sources from this survey were started by our group earlier (Tkachenko et al., 2015); in this paper, we discuss the sample of CVs obtained to date.

Below, we describe the procedure of the CV selection among the ROSAT X-ray sources using additional optical and infrared data from SDSS and WISE surveys. We provide a list of CVs selected in the 400d survey to date and discuss the properties of these objects. We also discuss the preliminary constraints on the X-ray luminosity function of CVs in the solar neighborhood obtained using this sample.

---

1Here and below all X-ray fluxes and luminosities are given in 0.5–2 keV energy band.
spectra in the 0.5–10 keV energy band look approximately similar in shape, irrespective of the CV type and state, and that the general form of these spectra can be approximately described by a power law within a photon index of $-1.6$.

**X-ray data**

In our work we used the ROSAT pointed data in the 0.5–2 keV energy band, at high galactic latitudes, which were used earlier to search for distant galaxy clusters (400d survey, Burenin et al. 2007). In 400d survey point X-ray sources were detected only in the central part of the ROSAT field of view at distances $< 18.5'$ from its center, where ROSAT angular resolution is better than $70''$ (PSF FWHM). The positional accuracy for an X-ray source is, on average, is better than $10''$ (at 95% confidence). We used 1605 ROSAT pointings at high Galactic latitudes $|b| > 25^\circ$. The CVs nearest to the Sun located within the Galactic disk must be observed at such latitudes.

The geometric area of the 400d survey for point sources is $436.7$ sq. deg. The geometric area of the 400d survey overlapping with SDSS photometric fields is $262.3$ sq. deg. Since the exposure distribution of ROSAT pointings is wide, the flux limit turns out to be different in different fields of the survey. Half and 5% of the geometric area are gathered at X-ray flux of $2.5 \cdot 10^{-14}$ and $8 \cdot 10^{-15}$ erg s$^{-1}$ cm$^{-2}$, respectively (Burenin et al. 2016b).

**Optical and Infrared data**

As it was discussed above, in total more than 37 000 X-ray sources were detected in the 400d survey, about 22 000 of them — in the fields where there is an overlap with SDSS photometric fields. Obviously, the complete optical identification of all X-ray sources from the 400d survey is too difficult, and additional data are required to select CVs. For these purposes, we used the data from the 12-th release of the SDSS (Alam et al. 2015) and the WISE infrared all-sky survey (Wright et al. 2010).

The stellar companions of the WDs in CVs are mostly low-mass ($< 1 M_\odot$) main-sequence stars (Knigge 2006). However, the WD in a CV and the accretion disk around it have a temperature no lower than $10^4$ K (see, e.g., Townsley and Gänsicke 2009), and, hence, are blue in the optical band. In the blue part of the optical spectrum and in the near ultraviolet, the CV spectrum must be always dominated by the emission from the WD and the accretion disk; therefore, this property can be used to select CVs in the optical band (see, e.g., Green et al. 1982; Szkody et al. 2002). For the selection of CV candidates, we used the criterion $u' - g' < 0.7$, which was used previously among other criteria in the SDSS to eliminate the WDs from the spectroscopic sample of quasars (Richards et al. 2002).

To eliminate a large number of quasars, which strongly contaminate the CV sample, we additionally discarded the objects with colors $w_1 - w_2 > 0.6$, where $w_1$ and $w_2$ are the photometric bands of the WISE infrared all-sky survey with central wavelengths of 3.4 and 4.6 $\mu$m (Wright et al. 2010). For the vast majority of stars (except for the cool T dwarfs) and, consequently, for the vast majority of CVs, this spectral range corresponds to the Rayleigh-Jeans part of the spectrum; therefore, the CV color must be $w_1 - w_2 \approx 0$.

We selected CV candidates with $g'$ magnitudes $< 20.0$. Even when the contribution of the accretion disk is small and the WD contribution dominates in the spectra of CVs, their absolute magnitudes are $M_{g'} \approx 12$ (Gänsicke et al. 2009; Revnivtsev et al. 2014). Therefore, the magnitude $g' \approx 20.0$ for such systems corresponds to a distance of $\approx 400$ pc, which is approximately equal to the thickness of the Galactic disk. The minimum absolute magnitude of CVs depends strongly on the WD mass and can reach $M_{g'} \approx 14$ for a WD with a mass of $\approx 1.2 M_\odot$ (Revnivtsev et al. 2014). Even for such systems the magnitude limit $g' < 20.0$ corresponds to a distance of $\approx 160$ pc, which also provides an appreciable search volume.

There are 53 objects satisfying the criteria discussed above in the 400d survey. Some of them (four objects) turned out to be previously known CVs. To identify the nature of the remaining objects, we carried out additional optical observations.

**OPTICAL OBSERVATIONS OF CV CANDIDATES**

The additional optical observations were carried out with the Russian–Turkish 1.5-m telescope (RTT-150) using the medium- and low-resolution TFOSC spectrophotograph and the 6-m (BTA) telescope at the Special Astrophysical Observatory of the Russian Academy of Sciences, where the SCORPIO-2 spectrophograph (Afanasyev, Moiseev 2005; 2011) was used for the observations. Recently, beginning in the fall of 2015, the observations have also been carried out with the 1.6-m AZT-33IK telescope at the Sayan Observatory of the Institute of Solar-Terrestrial Physics, the Siberian Branch of the Russian Academy of Sciences, using the new medium- and low-resolution ADAM spectrophograph (Afanasyev et al. 2016; Burenin et al. 2016a). In all cases, we used grisms or volume phase holographic gratings optimized for a range 4000–6000Å, which also includes the blue part of the spectrum starting from
Fig. 2. — Spectra of CVs detected in the 400d survey.
Fig. 3. Broadband spectrum of the CV 400d j154730.1+071151.

The black curve shows the RTT-150 spectrum (see Fig. 2). The red curve shows the model spectrum of a binary system which consist of an M2 V red dwarf and a white dwarf with a temperature of \( \approx 3 \cdot 10^4 \) K (WD0320−539). The measurements in the range 1500–2500˚A are taken from the observations with the GALEX orbital ultraviolet telescope (Martin et al., 2005). The histogram also indicates the photometric SDSS measurements in the \( u'g'r'i' \) bands.

3500–3700˚A. The spectral resolution was from 7 ˚A for SCORPIO-2 at the BTA telescope to 12 ˚A for TFOSC at the RTT-150.

The spectroscopic observations of objects from this programme were carried out during the last few years. We observed 38 objects, four of which turned out to be new, previously unknown CVs. The spectra for two of them (400d j001912.9 + 220736 and 400d j152212.8+080338) were later also obtained in the SDSS. The remaining objects turned out to be quasars at various redshifts, typically, at \( z = 1–2 \). Examples of the spectra for such quasars are given in Tkachenko et al. (2015). The spectra of CV found in our work are presented in Fig. 2. The spectra of 15 objects with magnitudes \( 19.5 < g' < 20 \) were not measured to date; this work will be continued.

THE CV SAMPLE

Basic information about the CVs in our sample is presented in the Table 1. Four of them turn out to be previously known CVs, using the optical observations described above, two of them were also independently detected in the SDSS during the spectroscopic observations of quasar candidates (Alam et al., 2015). The spectra of the CVs detected in 400d survey are presented in Fig. 2. The optical spectra of 400d j050146.2−035914, 400d j124325.7+025541, 400d j160002.4+331120 400d j204720.3+

Fig. 4. B-band light curve of the CV 400d j154730.1+071151 obtained with the Sayan observatory AZT-33IK telescope in March 2013.

000008 can be found in Burwitz et al. (1999), Stoke et al. (1983), Liu et al. (1999) and Szkoły et al. (2004), respectively (for more details, see also below).

Notes on individual objects

400d j050146.2−035914 (HY Eri)

The CV HY Eri=RX J0501.7-0359 was discovered in the ROSAT all-sky survey (Beuermann et al., 1999). It was found to be an eclipsing binary system with a magnetized WD, a polar (Burwitz et al., 1999). The overall spectrum of this system and its measured orbital period, 2.855 h, are also given in Burwitz et al. (1999).

Due to the absence of an accretion disk in the binary system, its optical brightness in the blue part of the spectrum is determined mainly by the emission from its hot WD. By assuming certain temperature (\( 10^4 \) K) and mass (0.6–0.8 M\(_{\odot}\)) of the WD and, consequently, its absolute magnitude \( M_g' \approx 11–12 \), we can estimate the distance to the binary system, \( D \approx 200–300 \) pc.

The binary system was detected in the infrared in the 2MASS all-sky survey with \( J = 16.67 \) (Skrutskie et al., 2006). In this part of the spectrum, the companion star makes a major contribution. Using the absolute magnitudes of CV companion stars tabulated in Knigge (2006), we can make another distance estimate for the binary system: \( D \approx 520 \) pc. In fact, the first distance estimate is only a lower limit, because the possible strong heating of the WD surface through accretion is not taken in account; therefore, the second distance estimate should be used.
source observed brightness is $r \ast r$ for the emission from this object near the B photometric band. Therefore, apart from the white and red dwarfs, an appreciable contribution of the emission from the accretion flow around the WD must also be present in the spectrum of this CV obtained with Sayan Observatory AZT-33IK telescope. 

We approximately decomposed the optical RTT-150 spectrum into two components corresponding to an M2 V dwarf (the spectrum WD0320-539 from the HST CALSPEC library of Pickles (1998), and a white dwarf without a strong magnetic field. This model also describes well the spectral flux library of Pickles (1998). In the same paper, it was suggested that the source is a dwarf nova, i.e., a CV with a WD without a strong magnetic field.

A broadband spectrum of another CV from our survey, 400d j154730.1+071151, is presented in Fig. 3. We can see that the $r$ band exhibits variability at a level of about 30% of the flux. Since the contributions of the WD and the accretion disk to the total flux from the binary system are insignificant in the $r$ band and assuming that the red dwarf in our binary system is a main-sequence star, we can roughly estimate the distance. The absolute magnitude of M2 V red dwarf in $r$ band is $M_r \approx 10.1$, the source observed brightness is $r' = 15.47$, therefore, the distance to the source can be estimated to be about 120 pc.

Note, that the X-ray luminosity of the binary system based on this distance estimate is $L_X \approx 2 \cdot 10^{29}$ erg s$^{-1}$, which roughly corresponds to the accretion rate of $5 \cdot 10^{-14} M_\odot$ for a WD of mass $\approx 0.5 M_\odot$ (if the X-ray luminosity accounts for a significant fraction of the bolometric luminosity of the accretion flow). Such an accretion rate is too low for a Roche-lobe-filling M2 V companion star. Thus, this object may be classified as the so-called “pre-cataclysmic variable”, i.e., a binary system where the mass transfer from the companion star onto the compact star through the inner Lagrangian point has not yet completely started.

400d j154730.1+071151

A broadband spectrum of another CV from our survey, 400d j154730.1+071151, is presented in Fig. 3. We can see that the $r$ band exhibits variability at a level of about 30% of the flux. Since the contributions of the WD and the accretion disk to the total flux from the binary system are insignificant in the $r$ band and assuming that the red dwarf in our binary system is a main-sequence star, we can roughly estimate the distance. The absolute magnitude of M2 V red dwarf in $r$ band is $M_r \approx 10.1$, the source observed brightness is $r' = 15.47$, therefore, the distance to the source can be estimated to be about 120 pc.

Note, that the X-ray luminosity of the binary system based on this distance estimate is $L_X \approx 2 \cdot 10^{29}$ erg s$^{-1}$, which roughly corresponds to the accretion rate of $5 \cdot 10^{-14} M_\odot$ for a WD of mass $\approx 0.5 M_\odot$ (if the X-ray luminosity accounts for a significant fraction of the bolometric luminosity of the accretion flow). Such an accretion rate is too low for a Roche-lobe-filling M2 V companion star. Thus, this object may be classified as the so-called “pre-cataclysmic variable”, i.e., a binary system where the mass transfer from the companion star onto the compact star through the inner Lagrangian point has not yet completely started.

400d j154730.1+071151

A broadband spectrum of another CV from our survey, 400d j154730.1+071151, is presented in Fig. 3. We can see that the $r$ band exhibits variability at a level of about 30% of the flux. Since the contributions of the WD and the accretion disk to the total flux from the binary system are insignificant in the $r$ band and assuming that the red dwarf in our binary system is a main-sequence star, we can roughly estimate the distance. The absolute magnitude of M2 V red dwarf in $r$ band is $M_r \approx 10.1$, the source observed brightness is $r' = 15.47$, therefore, the distance to the source can be estimated to be about 120 pc.

Note, that the X-ray luminosity of the binary system based on this distance estimate is $L_X \approx 2 \cdot 10^{29}$ erg s$^{-1}$, which roughly corresponds to the accretion rate of $5 \cdot 10^{-14} M_\odot$ for a WD of mass $\approx 0.5 M_\odot$ (if the X-ray luminosity accounts for a significant fraction of the bolometric luminosity of the accretion flow). Such an accretion rate is too low for a Roche-lobe-filling M2 V companion star. Thus, this object may be classified as the so-called “pre-cataclysmic variable”, i.e., a binary system where the mass transfer from the companion star onto the compact star through the inner Lagrangian point has not yet completely started.

400d j154730.1+071151

A broadband spectrum of another CV from our survey, 400d j154730.1+071151, is presented in Fig. 3. We can see that the $r$ band exhibits variability at a level of about 30% of the flux. Since the contributions of the WD and the accretion disk to the total flux from the binary system are insignificant in the $r$ band and assuming that the red dwarf in our binary system is a main-sequence star, we can roughly estimate the distance. The absolute magnitude of M2 V red dwarf in $r$ band is $M_r \approx 10.1$, the source observed brightness is $r' = 15.47$, therefore, the distance to the source can be estimated to be about 120 pc.

Note, that the X-ray luminosity of the binary system based on this distance estimate is $L_X \approx 2 \cdot 10^{29}$ erg s$^{-1}$, which roughly corresponds to the accretion rate of $5 \cdot 10^{-14} M_\odot$ for a WD of mass $\approx 0.5 M_\odot$ (if the X-ray luminosity accounts for a significant fraction of the bolometric luminosity of the accretion flow). Such an accretion rate is too low for a Roche-lobe-filling M2 V companion star. Thus, this object may be classified as the so-called “pre-cataclysmic variable”, i.e., a binary system where the mass transfer from the companion star onto the compact star through the inner Lagrangian point has not yet completely started.
liminary estimates of the constraints on the luminosity function, let us assume that the remaining systems have a low X-ray luminosity. In this case, their absolute magnitudes must be near minimum value of $M_g \approx 12$ which is defined by the presence of a WD in the system (Revnivtsev et al., 2014). In these systems, the accretion rate onto the WD must be low, and their orbital periods must be not far from the period minimum. Therefore, this value of $M_g$ agrees well with the estimate of $M_g \approx 11.6$ for systems with periods near the minimum (Gänsicke et al., 2009).

Note, that signatures of WD emission are clearly seen in the spectra of two systems (400d j001912.9+220736, 400d j160547.5+240524, see Fig. 2), which is expected for such systems (Gänsicke et al., 2009). The system 400d j160002.4+331120 is known to have a short orbital period, $P_{orb} = 107$ min, which is quite close to the period minimum (86 min). Therefore, its absolute magnitude should also be close to the above one.

The X-ray luminosities that are derived for systems with unknown distances under the assumption of $M_g \approx 12$ are given in the table and marked by asterisks. The distance estimates for these systems turn out to be within the range 200–300 pc. Some of the systems, on average, cannot be much higher, because, in this case, the objects should be located at appreciably larger distances, but at high Galactic latitudes the space density of sources at distances larger than the thickness of the Galactic disk drops rapidly.

Based on these data, we can obtain preliminary constraints on the CV X-ray luminosity function. For simplicity, we will assume that the flux limit for X-ray sources in the 400d survey is $2.5 \cdot 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ irrespective of the ROSAT pointing field, and that the area overlapping with the SDSS is 262.3 sq. deg. The dependence of the density of sources in the Galactic disk on the perpendicular distance from the Galactic plane, $\rho(z) = \rho_0 e^{-|z|/h}$, can be taken into account trough the calculation of generalized volume, as it was done by Tinney et al. (1993) and Pretorius et al. (2007b). We will assume that the exponential scale height of the Galactic disk for our CVs is 260 pc, which corresponds to the disk scale height for old, short-period systems (Pretorius et al., 2007a).

It should be also noted that only systems with $m_g < 20$ are included in our sample. This constraint does not affect the selection of systems located at distances less than about 400 pc, because there is a minimum absolute magnitude $M_g \approx 12$ for CVs (Revnivtsev et al., 2014). For systems located at larger distances, the selection probability depends not only on the X-ray flux but also on the $g'$ magnitude. Therefore, the system 400d j050146.2–035914 (HY Eri), whose distance can be estimated to be 520 pc, is not taken into account in the estimates below.

The sample incompleteness can be taken into account statistically, appropriately increasing the measurement errors. As was pointed out above, at present we carried out optical observations for 21 out of the 36 selected objects with magnitudes $19.5 < g' < 20$, with two previously unknown CVs having been detected among them. Therefore, the number of previously unknown CVs among the remaining 15 objects can be estimated to be, on average, about 1.4. It can be seen from the table that these CVs will most likely have luminosities $L_X \approx 10^{30}$ erg s$^{-1}$.

Six systems from our sample are found in in the range of X-ray luminosities $3 \cdot 10^{29}$–$3 \cdot 10^{30}$ erg s$^{-1}$. Taking into account all mentioned above, we obtain the following constraint on the CV space density based on this sample: $\rho_0 = 1.0 \pm 0.4 \cdot 10^{-5}$ pc$^{-3}$. Only one system, 400d j154730.1+071151, with a luminosity close to the upper boundary of the X-ray luminosity range $3 \cdot 10^{28}$–$3 \cdot 10^{29}$ erg s$^{-1}$ is found in this luminosity range. In this case, the upper limit on the CV space density for this range is $\rho_0 < 4.1 \cdot 10^{-5}$ pc$^{-3}$ (at 95% confidence). However, this system is apparently a pre-cataclysmic variable. If such systems are not considered as CVs, then no object is found in the
luminosity range $3 \cdot 10^{28} - 3 \cdot 10^{29}$ erg s$^{-1}$ and the limit on the CV space density is then $\rho_0 < 2.7 \cdot 10^{-5}$ pc$^{-3}$.

Our constraints on the X-ray luminosity function of CVs are shown with solid red crosses in Fig. 5. The blue circles indicate the measurements of the X-ray luminosity function based on RXTE data (Sazonov et al., 2006) recalculated to the 0.5–2 keV energy band under the assumption of a power-law spectrum $dN/dE \propto E^{-1.6}$; the dotted crosses show the constraints on the luminosity function from the ROSAT North Ecliptic Pole survey [Pretorius et al., 2007b]. It can be seen from the figure that our constraint on the CV space density near $L_X \approx 10^{30}$ erg s$^{-1}$ agrees well with that from [Pretorius et al., 2007b]. Note that we obtain significantly stronger upper limit on the CV space density near an X-ray luminosity $L_X \approx 10^{29}$ erg s$^{-1}$.

**DISCUSSION**

We present a sample of CVs detected among the X-ray sources of the 400 square degree (400d) survey. As it was shown above, this X-ray survey is well suited to search for low X-ray luminosity CVs. Note that among the systems selected in 400d survey, there is an appreciable fraction of systems whose spectra clearly show signatures of the WD emission (see Fig. 2), which is expected for systems with a low accretion rate (Gänsicke et al., 2009). Based on this X-ray sample of CVs, we obtained preliminary constraints on the X-ray luminosity function of CVs in the range of low X-ray luminosities, $L_X \approx 10^{29} - 10^{30}$ erg s$^{-1}$. From the comparison of our constraints with the luminosity function at $L_X > 10^{31}$ erg s$^{-1}$ measured previously (Sazonov et al., 2006), we conclude that its logarithmic slope is less steep at low luminosities (see Fig. 5).

The presented results are preliminary ones. They can be significantly improved if more or less reliable distance estimates will be obtained for a larger number of systems and if the statistically complete sample will be expanded to include system with a lower optical brightness. We are going to continue this work in future.

Our constraints on the CV luminosity function can be compared with theoretical estimates of the space density of these objects. For example, de Kool (1992) estimated the space density of all CVs to be $\approx 0.5 - 2 \cdot 10^{-4}$ pc$^{-3}$ (recalculated to the Galaxy age of 10 Gyr). As follows from Fig. 4, we can eliminate such a number of CVs in the investigated luminosity range. This may imply, for example, that a large number of CVs have an even lower X-ray luminosity. It should also be taken in account that the CV luminosity can change in a wide range due to accretion instability.

From our estimates of the CV X-ray luminosity function, we conclude that several thousand CVs will be detected in the future Spectrum-Röentgen-Gamma all-sky X-ray survey with eROSITA telescope at high Galactic latitudes, which will allow to significantly improve the measurements of their X-ray luminosity function at X-ray luminosities $L_X < 10^{31}$ erg s$^{-1}$. Further studies of CV samples at lower luminosities, $L_X < 10^{29}$ erg s$^{-1}$, will possibly allow to detect large number of systems at late post-bounce evolutionary stages and to measure their space density.

This work was supported by the Russian Foundation for Basic Research (project no. 13-02-00741-a) and grant NSh-6137.2014.2. The calculations of the area of the 400d X-ray survey used here were supported by RSF grant no. 14-22-00271. The observations at the 6-meter BTA telescope were carried out with the financial support of the Ministry of Education and Science of the Russian Federation (agreement no. 14.619.21.0004, project ID RFMEFI61914X0004).

**REFERENCES**

2. S. Alam, F. D. Albareti, C. Allende Prieto, F. Anders, S. F. Anderson, T. Anderton, et al., Astrophys. J. Suppl. Ser. 219, 12 (2015).
3. S. V. Antipin, Information Bulletin on Variable Stars 4343, 1 (1996).
4. K. Aizu, Progress of Theoretical Physics 49, 1184 (1973).
5. A. Aviles, S. Zharikov, G. Tovmassian, R. Michel, M. Tapia, M. Roth, V. Neustroev, et al., Astrophys. J. 711, 389 (2010).
6. V.L. Afanasiev, A.V. Moiseev, Pis’ma v Astron. Zhurn. 31, 194 (2005); [Astronomy Letters, 31, 194]
7. V.L. Afanasiev, A.V. Moiseev, Balt. Astr. 20, 363 (2011).
8. V.L. Afanasiev, S.N. Dodonov, V.R. Amirkhanyan, A.V. Moiseev, Astrophysical Bulletin, in press (2016); arXiv:1611.07572.
9. K. Byckling, K. Mukai, J. R. Thorstensen, J. P. Osborne, Mon. Not. R. Astron. Soc. 408, 2298 (2010).
10. K. Beuermann, H.-C. Thomas, Advances in Space Research 13, (12)115 (1993).
11. K. Beuermann, H.-C. Thomas, K. Reinsch, A. D. Schwope, J. Trümper, W. Voges, Astron. Astrophys. 347, 47 (1999).
12. V. Burwitz, K. Reinsch, K. Beuermann, H.-C. Thomas, Annapolis Workshop on Magnetic Cataclysmic Variables, ASP Conference Series, v. 157, ed. by C. Hellier and K. Mukai, 127 (1999).
13. R.A. Burenin, A. Vikhilin, A. Hornstrup et al., Astrophys. J. Suppl. Ser. 172, 561 (2007).
14. R.A. Burenin, A.L. Amvrosiyev, M.V. Eselechv, et al., Pis’ma v Astron. Zhurn. 42, 333 (2016) [Astronomy Letters 42, 295 (2016)].
15. Burenin et al., Pis’ma v Astron. Zhurn., in preparation (2016b).
16. M. de Kool, Astron. Astrophys. 261, 188 (1992).
17. J. Faulkner, Astrophys. J. 170, L99 (1971).
18. (B. T. Gänscicke, M. Dillon, J. Southworth, J. R. Thorstensen, P. Rodriguez-Gil, A. Aungwerojwit, et al.), Mon. Not. R. Astron. Soc. 397, 2170 (2009).
19. R. F. Green, D. H. Ferguson, J. Liebert, M. Schmidt, Astron. Soc. of the Pacific 94, 560 (1982).
20. S. L. Hawley, K. R. Covey, G. R. Knapp, D. A. Golimowski, X. Fan, S. F. Anderson, et al., Astron. J. 123, 3409 (2002).
21. S. B. Howell, L. A. Nelson, S. Rappaport, Astrophys. J. 550, 897 (2001).
22. C. Knigge, Mon. Not. R. Astron. Soc. 373, 484 (2006).
23. C. Knigge, I. Baraffe, and J. Patterson, Astrophys. J. Suppl. Ser. 194, 28 (2011).
24. U. Kolb, Astron. Astrophys. 271, 149 (1993).
25. S. P. Littlefair, V. S. Dhillon, T. R. Marsh, B. T. Gänscicke, J. Southworth, I. Baraffe, C. A. Watson and C. Copperwheat, Mon. Not. R. Astron. Soc. 388, 1592 (2008).
26. W. Liu, J. Y. Hu, X. H. Zhu, Z. Li, Astrophys. J. Suppl. Ser. 122, 243 (1999).
27. D. C. Martin, J. Fanson, D. Schiminovich, P. Morrissey, P. G. Friedman, T. A. Barlow, et al., Astrophys. J. 619, L1 (2005).
28. R. Novak, Information Bulletin on Variable Stars 4489, 1 (1997).
29. B. Paczynski, Acta Astronomica 31, 1 (1981).
30. A. J. Pickles, PASP 110, 863 (1998).
31. M. L. Pretorius, C. Knigge, U. Kolb, Mon. Not. R. Astron. Soc. 374, 1495 (2007a).
32. M. L. Pretorius, C. Knigge, D. O’Donoghue, J. P. Henry, I. M. Gioia, C. R. Mullis, Mon. Not. R. Astron. Soc. 382, 1279 (2007b).
33. M. L. Pretorius and C. Knigge, Astron. Astrophys. 419, 1442 (2012).
34. M. L. Pretorius and K. Mukai, Mon. Not. R. Astron. Soc. 442, 2580 (2014).
35. M. Revnivtsev, E. Churazov, S. Sazonov, W. Forman, C. Jones, Astron. Astrophys. 490, 37 (2008a).
36. M. Revnivtsev, S. Sazonov, R. Krivonos, H. Ritter, R. Sunyaev, Astron. Astrophys. 489, 1121 (2008b).
37. M. Revnivtsev, S. Sazonov, E. Churazov, W. Forman, A. Vikhlinin, R. Sunyaev, Nature 458, 1142 (2009).
38. M.G. Revnivtsev, E.V. Filippova, V.F. Suleimanov, Pis’ma v Astron. Zhurn. 40, 196 (2014). [Astronomy Letters, 40, 177]
39. H. Ritter, U. G. Kolb, Astron. Astrophys. 404, 301 (2003).
40. G. T. Richards, X. Fan, H. J. Newberg, M. A. Strauss, D. E. Vanden Berk, D. P. Schneider, et al., Astron. J. 123, 2945 (2002).