Relation between the X-ray and Optical Luminosities in Binary Systems with Accreting Nonmagnetic White Dwarfs

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Abstract — We investigate the relation between the optical (g-band) and X-ray (0.510 keV) luminosities of accreting nonmagnetic white dwarfs. According to the present-day counts of the populations of star systems in our Galaxy, these systems have the highest space density among the close binary systems with white dwarfs. We show that the dependence of the optical luminosity of accreting white dwarfs on their X-ray luminosity forms a fairly narrow one-parameter curve. The typical half-width of this curve does not exceed 0.2–0.3 dex in optical and X-ray luminosities, which is essentially consistent with the amplitude of the aperiodic flux variability for these objects. At X-ray luminosities \(L_x \sim 10^{32}\) erg s\(^{-1}\) or lower, the optical g-band luminosity of the accretion flow is shown to be related to its X-ray luminosity by a factor \(\sim 2–3\). At even lower X-ray luminosities (\(L_x \sim 10^{30}\) erg s\(^{-1}\)), the contribution from the photosphere of the white dwarf begins to dominate in the optical spectrum of the binary system and its optical brightness does not drop below \(M_g \sim 13–14\). Using the latter fact, we show that in current and planned X-ray sky surveys, the family of accreting nonmagnetic white dwarfs can be completely identified to the distance determined by the sensitivity of an optical sky survey in this region. For the Sloan Digital Sky Survey (SDSS) with a limiting sensitivity \(m_g \sim 22)\), this distance is \(\sim 400–600\) pc.

Key words: X-ray and optical luminosities, binary systems, white dwarfs

INTRODUCTION

Close binary systems with white dwarfs (WDs) constitute the largest family of star systems with compact objects onto which matter is accreted. The universally accepted name of such binary systems, cataclysmic variables (CVs), owes its origin to significant brightness variations during their outbursts, which were the reason for isolating this class of objects (see, e.g., Warner 2003). The CV brightness variations are currently believed to result from the instability of mass transfer in accretion disks around compact objects (Lasota 2001). This turns them into very important laboratories to investigate the turbulent and magnetic viscosities in space plasmas.

The interest in accreting WDs has only increased in recent years owing to the fact that such binary systems are among the possible progenitors of type Ia supernovae (Hachisu, Kato, & Nomoto 1996), which, in turn, are used for cosmological studies (Riess et al. 1998). Various calculations show that the longterm evolution of WD during the accretion of matter can lead both to an increase in its mass and an explosion as a supernova and to the ejection of part of its envelope and long-term mass loss (Prialnik & Kovetz 1995; Yaron et al. 2005). The time scales of the long-term evolution of WDs are very large (see, e.g., the review by Howell, Nelson, & Rappaport 2001). Therefore, these questions can be answered only by studying the whole populations of binary systems with WDs and this means that a criterion for their efficient selection among the various objects in the sky is needed.

CVs radiate in a wide energy range: from the infrared and optical bands to the hard X-ray band. The main emission components in the case of white dwarfs with a weak magnetic field are: the companion star (as a rule, a dwarf star with temperatures below 3500–4000 K; see, e.g., the review by Knigge, Baraffe, & Patterson 2011), the accretion disk radiating in the optical and ultraviolet bands, the WD with an effective temperature of at least 8000–10 000 K; see, e.g., the review by Knigge, Baralle, & Patterson 2011, the accretion disk radiating in the optical and ultraviolet bands, the WD with an effective temperature of at least 8000–10 000 (Townesley & Bildsten 2003; Townesley, Gansicke 2009), and the boundary layer near the WD surface radiating in X-rays (see e.g. Pringle & Savonije 1979; Patterson & Raymond 1985).

If the rate of mass transfer through all parts of the accretion flow (accretion disk, boundary layer) is the same, then there must exist a certain relation between their luminosities, which can facilitate the binary system identification. However, the simple picture of an accretion flow in the case of dwarf novae in the off (quiescent) state is complicated by the fact that the rates of mass transfer in different parts of the accretion flow and, consequently, their luminosities in different en-
The optical emission from a hot accretion disk (Pretorius, Knigge, & Kolb, 2007; Drake et al., 2009). Observational selection effects (see e.g. Gansicke, 2004; Pretorius & Knigge, 2012) are present in most of the accessible spectral bands, including the X-ray one. The X-ray luminosity of accreting WDs associated with their much larger (compared to optical sky surveys) fraction in the total population of detected sources and with cleaner imaging for accreting WDs associated with their much larger (compared to optical sky surveys) fraction in the total population of detected sources and with cleaner imaging for accreting WDs associated with their much larger (compared to optical sky surveys) fraction in the total population of detected sources and with cleaner imaging for accreting WDs associated with their much larger (compared to optical sky surveys) fraction in the total population of detected sources and with cleaner imaging for accreting WDs.

### Table 1. Parameters of the dwarf novae in the off state whose X-ray luminosities were determined here

| Source          | Distance, $D$ (pc) | $m_g$ (mag) | Flux $0.5-2$ keV | Flux $2-10$ keV | log $L_{\text{x}}$, erg s$^{-1}$ | Observatory | Dates         |
|-----------------|-------------------|-------------|-----------------|----------------|-------------------------------|-------------|---------------|
| SW UMa          | 164 ± 22          | 16.87        | 5.6 ± 0.9       | 5 ± 2          | 30.53                         | SWIFT       | 2011.12.18-19 |
| T Leo           | 101 ± 13          | 14.86        | 65 ± 2          | 94 ± 3         | 31.28                         | ASCA        | 1998.12.13    |
| BZ UMa          | 228 ± 63          | 16.37        | 21 ± 1          | 43 ± 3         | 31.52                         | SWIFT       | 2012.08.24-25 |
| VW Hya          | 64 ± 20           | 13.9V        | 32 ± 2          | 42 ± 3         | 30.55                         | ASCA        | 1993.11.08    |
| WX Hya          | 260 ± 64          | 14.7V        | 29 ± 3          | 50 ± 8         | 31.80                         | Chandra     | 2002.07.28-29 |
| SU UMa          | 261 ± 65          | 14.6V        | 20 ± 2          | 39 ± 5         | 31.68                         | ASCA        | 1997.04.12-13 |
| EF Tuc          | 346 ± 150         | 14.5V        | 20 ± 1          | 67 ± 5         | 31.09                         | SWIFT       | 2008.09.12    |
| RXJ1831         | 980 ± 630         | 17.04        | 5.7 ± 0.7       | 14 ± 2         | 32.35                         | ASCA        | 1998.09.19-20 |
| WW Cet          | 158 ± 43          | 14.68        | 68 ± 4          | 125 ± 3        | 31.76                         | ASCA        | 1996.12.24-25 |
| V405 Peg        | 149 ± 26          | 16.79        | 8.9 ± 0.8       | 15 ± 2         | 30.80                         | SWIFT       | 2008-2012     |
| TW Pic          | 230 ± 105         | 15.2V        | 40 ± 1          | 149 ± 7        | 32.07                         | SWIFT       | 2007.11.13-12.31 |

The optical $g$-band brightness of the binary systems was taken from the SDSS catalog (Ahn et al., 2012). The optical brightness measurements for the binary systems marked by letter V are given in the V band (the V-band brightness distribution along the accretion disk radius is quiescence obtained by eclipse mapping (see, e.g., Wood et al., 1986). This distribution turns out to be considerably flatter than is expected for optically thick disks with a constant (along the radius) accretion rate (Shakura & Sunyaev, 1973). Nevertheless, as was shown, for example, by Bird (2000), if the inner boundary of an optically thick disk exceeds considerably the WD size, then this conclusion may turn out to be incorrect as a result of disk destruction by the WD magnetic field, as in the case of intermediate polars, or as a result of disk evaporation (Meyer & Meyer-Hofmeister, 1994). There are observational evidences Kuulkers et al. (2011); Revnivtsev et al. (2012); Balman & Revnivtsev (2012) that the inner disks of dwarf novae in quiescence pass to the state of an optically thin accretion flow with a plasma temperature of the order of the virial one and radiate mainly in X rays. Consequently, the relation between the rates of mass accretion through an optically thick accretion disk and onto the WD surface should be determined from observations in all of the accessible spectral bands, including the X-ray one.

Almost any CV detection strategy suffers from observational selection effects (see e.g. Gansicke, 2004; Pretorius, Knigge, & Kolb, 2007; Drake et al., 2009). The optical emission from a hot accretion disk ($T > 6000 – 10000$ K) is difficult to distinguish in color from hot stars. Only the presence of strong Balmer emission lines in the spectra, along with the emission in He II, CH, and NII lines (Bowen blend), can serve as direct evidence. In optical sky surveys, the systems are often identified as CVs if they exhibit outbursts like dwarf novae or eclipses with a period typical of CVs or the color is bluer than some color in the short-wavelength part of the optical spectrum (Green et al., 1982) etc. (see, e.g., the strategy in Szkody et al., 2002). Among the optical sky surveys, the SDSS is presently perhaps least affected by observational selection effects; at the same time, record sensitivities over large sky regions were achieved in it (Szkody et al., 2011). The disclosure of the long-predicted population of CVs with short orbital periods has already become the result of searching for CVs in the SDSS (Gansicke et al., 2009). In the currently existing X-ray sky survey, the number of CVs is small (Verbunt et al., 1997; Schw Hoe et al., 2002; Gansicke et al., 2005; Sazonov et al., 2006; Revnivtsev et al., 2008; Pretorius & Knigge, 2012; Pretorius, Knigge, & Schw Hoe, 2013) and is limited to the systems with the highest X-ray luminosities/accretion rates, as a rule, with magnetic WDs. Nevertheless, X-ray sky surveys have a significant advantage in searching for accreting WDs associated with their much larger (compared to optical sky surveys) fraction in the total population of detected sources and with cleaner...
The goal of this paper is to systematize our knowledge of the relation between the X-ray and optical luminosities of accreting nonmagnetic WDs for their subsequent use in analyzing sky surveys. As a first step in this direction, we restricted ourselves only to CVs with nonmagnetic WDs. Such a selection allows the additional complexities associated with the contribution of cyclotron radiation to the optical and infrared continuum of the sources to be avoided. We investigate the systems in their typical states, i.e., in those where they spend the vast bulk of their time and will most likely be detected in random sky surveys. For systems with a low accretion rate, dwarf novae, we take the observations only in their quiescent/off state.

**SAMPLE OF SOURCES**

To investigate the broadband emission from nonmagnetic CVs, we combine three samples of sources: dwarf novae from the ROSAT all-sky and North Ecliptic Pole surveys [Pretorius & Knigge 2012], dwarf novae with measured parallaxes [Byckling et al. 2010], and low-luminosity nonmagnetic CVs discovered in the SDSS [Reis et al. 2013]. Since [Pretorius & Knigge 2012] provided only the 0.5–2 keV fluxes for the sample of sources from the ROSAT sky surveys, we performed an additional analysis of the observational data from X-ray observatories capable of covering the energy range 0.5–10 keV (ASCA, SWIFT, Chandra). The SWIFT and ASCA data were analyzed with the LHEASOFT software package. The Chandra data were processed with the CIAO 4.5 software package. The energy spectra of the sources were analyzed with the XSPEC code [Arnaud 1996]. To fit the data, we used the model of a multitemperature optically thin plasma $c_{\nu \nu \nu} kT$, which is commonly used to describe the emission from such systems. The measured 0.5–2 keV and 2–10 keV fluxes from the sources are given in the Table 1.

**RESULTS**

The correlations between the X-ray and optical fluxes from CVs have been the subject of studies starting from the systematic surveys of the Einstein (see e.g. Patterson & Raymond 1985) and ROSAT (van Teeseling, Beuermann, & Verbunt 1996; Verbunt et al. 1997; Schwolle et al. 2002) observatories. However, the results obtained in recent years allow one to estimate the distances to the systems being investigated more reliably, to separate the systems in outbursts from those in quiescence more reliably, and to study fainter systems. New data have already revealed various correlations between observed quantities (for example, between the orbital periods of CVs and their maximum brightness; Patterson 2011).

Figure 1 presents the X-ray and optical luminosity measurements for dwarf novae in quiescence from the samples of sources being investigated. The X-ray luminosities of the sources from [Byckling et al. 2010] were recalculated to the 0.5–10 keV energy band using a coefficient $L_{0.01−100\text{keV}}/L_{0.5−10\text{keV}} \sim 1.6$.

When analyzing the dependence presented in Fig.
We should take into account the fact that the instantaneous optical and X-ray fluxes have an uncertainty related to the stochastic flux variability of the sources. The amplitude of this variability was estimated from numerous X-ray observations of the dwarf nova SS Cyg in quiescence (the X-ray luminosity in this state is $L_x \sim 2 \times 10^{32}$ erg s$^{-1}$) to be about 30%. It can be seen from Fig. 1 that the relation between the X-ray luminosity of nonmagnetic accreting WDs and their optical luminosity is fairly close, actually unambiguous within the amplitude of their chaotic variability.

The $L_{opt} - L_X$ relation in Fig. 1 has three main peculiarities:

1. There are no dwarf novae in the off/quiescent state with X-ray luminosities of more than $L_x \sim 10^{32}$ erg s$^{-1}$, while there are no obstacles to the detection of such systems in various sky surveys. Accreting WDs with high X-ray luminosities are actually observed in various sky surveys, for example, in the ROSAT [Pretorius, Knigge, & Schwepe 2013], RXTE [Revnivtsev et al. 2004], Sazonov et al. [2006], INTEGRAL [Revnivtsev et al. 2008], Krivonos et al. 2012, and SWIFT (?) sky surveys, but they all are magnetic WDs. The transition at high mass accretion rates in the accretion disk to a state with a different, much lower fraction of the X-ray luminosity in the bolometric luminosity of the binary system is probably responsible for the absence of dwarf novae with high luminosities.

2. At X-ray luminosities $L_{0.5-10keV} \sim 10^{31-32}$ erg s$^{-1}$ (at accretion rates onto the WD of $\sim 10^{-12-11} M_\odot$ yr$^{-1}$), the ratio $L_{opt,g}/L_{0.5-10keV}$ is close to 2-3. The behavior of the optical/X-ray luminosity ratio at $L_x \sim 10^{31}$ erg s$^{-1}$ suggests that at this or lower luminosities the accretion rate onto the WD surface (which we observe as the X-ray luminosity of CVs) is close to that in the outer accretion flow (which we observe as the optical luminosity of CVs). A more detailed study of the shape of the relation between the optical luminosity of the accretion flow and its X-ray luminosity requires a careful decomposition of the total optical luminosity into its individual components, such as the contribution from the WD photosphere and the contribution from the companion star, and a proper allowance for the bolometric corrections for various components.

3. At X-ray luminosities $L_x < 10^{30}$ erg s$^{-1}$, the optical luminosity ceases to depend on the X-ray one. This peculiarity stems from the fact that the
The rate of mass accretion onto the compact object in dwarf novae in quiescence (\(\sim\) its X-ray luminosity) is comparable to the rate of mass transfer to the outer accretion disk (\(\sim\) the optical luminosity of the accretion flow). As a clear illustration of this fact, Fig. 2 presents a broadband spectrum of the dwarf nova BZ UMa with approximate designations of its individual emission components. The spectrum of a red dwarf with a temperature of 2950 K was taken from the library of spectra by Pickles (1998). We calculated the spectrum for a WD atmosphere of solar chemical composition using our new computational code (for more details, see Ilargimov et al. 2003; Suleimanov & Werner 2007; Suleimanov et al. 2013).

**PREDICTION FOR X-RAY SKY SURVEYS**

The existence of a close relation between the X-ray and optical luminosities of dwarf novae (in quiescence) simplifies considerably the approaches to identifying such X-ray sources being discovered in new sky surveys. A simple analytical fit to the observed data points in logarithmic coordinates (without including the uncertainty in the quantities) can be represented by the function

\[
M_g = -2.5 \log \left( 1.05 \times 10^{-5} + 8.4 \times 10^{-6} L_{x,30} \right),
\]

where \(L_{x,30} = L_x/10^{30}\) erg s\(^{-1}\) is the sources X-ray luminosity and \(M_g\) is its g-band absolute magnitude. The predictions of X-ray and optical fluxes for nonmagnetic dwarf novae using this dependence for various distances are presented in Fig. 3. It is clearly seen from the plots that the ratio of the optical and X-ray fluxes from dwarf novae in a sky survey can actually cover a range of approximately two orders of magnitude (which is observed; see, e.g., Schwope 2012), such a spread arises from the mixing of sources with different luminosities at different distances and from the nonlinear dependence of their optical luminosity on the X-ray one (note that this situation differs greatly from the case of active galactic nuclei; see, e.g., Sazonov et al. 2012). The most important conclusion that we can draw from this plot is that at a fixed sensitivity \(m_{g,\text{lim}}\) of the optical survey accompanying the X-ray survey, there exists some volume in which we can identify the complete set of all dwarf novae detected in the X-ray band. Indeed, since the limiting optical brightness of CVs at an arbitrarily low accretion rate does not drop below some value (\(M_{g} \sim 13\) for WDs with masses 0.6–0.8 \(M_\odot\)), any, arbitrarily weakly accreting WDs will be detected up to distances log \(d_{\text{pc}} \sim 0.2(m_{g,\text{lim}} - 8)\). For \(m_{g,\text{lim}} \sim 20\), the boundary of the volume in which we must assuredly detect any accreting nonmagnetic WDs is about 250 pc. For a sensitivity \(m_{g,\text{lim}} \sim 22.2\) corresponding to the SDSS, this boundary is pushed to \(\sim 690\) pc. It should be noted, however, that this limit depends significantly on the WD mass. For example, at WD mass of 1.2 \(M_\odot\), its optical brightness can be \(M_{g} \sim 14.4\) and the boundary of the viewed volume is reduced to \(\sim 360\) pc. This fact should be explicitly taken into account when analyzing the completeness of the sample of accreting binary systems.
CONCLUSIONS
We investigated the relation between the optical and X-ray luminosities for a wide sample of accreting nonmagnetic WDs (dwarf novae) in quiescence. We showed the following:

- The relation between the optical and X-ray luminosities of dwarf novae (in quiescence) forms a fairly narrow one-parameter curve. The overwhelming majority of the investigated system fit within 0.2 dex around the fitting curve. At X-ray luminosities $L_{0.5-10\text{keV}} \sim 10^{34} \text{erg s}^{-1}$ (at accretion rates onto WD $\sim 10^{-12} M_{\odot} \text{yr}^{-1}$), the ratio $L_{\text{opt,g}}/L_{0.5-10\text{keV}}$ is close to 23.

- The X-ray luminosity $(2-3) \times 10^{30} \text{erg s}^{-1}$ separates the regions in which the optical luminosity of a binary system with an accreting WD depends on its X-ray luminosity and the region in which the optical luminosity of the binary system is virtually independent of it. At low X-ray luminosities, the contribution from the WD photosphere dominates in the optical luminosity of a binary system.

- Based on this fact, we may conclude that the family of accreting nonmagnetic WD can be completely identified to the distances of 400–600 pc determined by the sensitivity $m_{g,\text{lim}}$ of the optical sky survey in this region in current and future X-ray sky surveys.

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ASTRONOMY LETTERS Vol. 40 No. 4 2014
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