An Empirical Correlation of $T_{\text{max}} - M_{\text{WD}}$ of Dwarf Novae and the Average White Dwarf Mass in Cataclysmic Variables in the Galactic Bulge

Zhuo-li Yu, Xiao-jie Xu ©, Xiang-Dong Li, Tong Bao, Ying-xi Li, Yu-chen Xing, and Yu-fu Shen
School of Astronomy and Space Science and Key Laboratory of Modern Astronomy and Astrophysics, Nanjing University, Nanjing, 210093, People’s Republic of China; xunj@nju.edu.cn
Received 2017 November 1; revised 2017 December 18; accepted 2017 December 27; published 2018 February 5

Abstract

The mean white dwarf (WD) mass in the Galactic bulge cataclysmic variables (CVs) was measured by applying the shock temperature-WD mass correlation of magnetic cataclysmic variables (mCVs) to the Galactic bulge X-ray emission (GBXE) spectra. However, the resulting mean WD mass is lower than that of the local CVs. This discrepancy could be explained by the dominating sources in the GBXE, which are non-mCVs instead of mCVs. In this work, we conduct a thorough investigation of the X-ray spectra of local DNe from the Suzaku archives and derive semi-empirical correlations between the shock temperature $T_{\text{max}}$, the flux ratio of Fe xxvi-Ly$\alpha$ to Fe xxv–He$\alpha$ lines, and WD mass for quiescent, nonmagnetic CVs. By applying these correlations to the GBXE, we derive the average WD mass of CVs in the Galactic bulge to be $0.81 \pm 0.07 M_\odot$. This value is consistent with previous optical measurements of WD mass in local CVs.

Key words: Galaxy: bulge – novae, cataclysmic variables – X-rays: binaries

1. Introduction

A cataclysmic variable (CV) is a binary star in which a white dwarf (WD) accretes matter from a main-sequence or a subgiant star through Roche-lobe overflow. Subgroups of CVs include magnetic CVs (mCVs) and nonmagnetic ones based on the magnetic field strengths of the WDs (Warner 1995; Frank et al. 2002). About 10%–20% of CVs are mCVs, and the others are non-mCVs, more specifically, dwarf novae (DNe; e.g., Liebert et al. 2003; Pretorius et al. 2013). With X-ray luminosity $\sim 10^{30–34}$ erg s$^{-1}$, CVs are important X-ray emitters in the Galaxy (e.g., Sazonov et al. 2006; Revnivtsev et al. 2009a; Warwick 2014). In an mCV, for example, intermediate polars (IPs), matter from the companion star is heated by a strong shock and emits X-rays before falling onto the WD surface along the WD magnetic field lines. In a nonmagnetic CV, on the other hand, X-ray photons are mainly from a boundary layer near the WD surface, where accreted matter is heated by either a strong shock or a series of weak shocks (e.g., Frank et al. 2002). For both subclasses of CVs, the X-ray spectra include a continuum from multi-temperature optical-thin thermal plasma and prominent emission lines (e.g., the H-like and He-like Fe lines near 7 keV). The spectra could be well fitted by an absorbed cooling flow model (mkcflow in Xspec; Mushotzky & Szynkowski 1988) with an additional intrinsic absorption in some cases (Mukai et al. 2003).

The WD in a CV could hardly retain its accreted matter (e.g., Prialnik & Kovetz 1995; Yaron et al. 2005; Liu & Li 2016). As a result, the present WDs in CVs could reflect the initial properties of WDs when the CV was formed, thus they could be used to constrain (binary) star evolution theories. Moreover, CVs are closely related to the possible progenitors of type Ia supernovae, as both of them involve accreting WDs. Traditionally, the WD masses in CVs were measured in the optical/UV band (e.g., Friend et al. 1990; Mason et al. 2001; Zorotovic et al. 2011), and the results suggest an average WD mass of $0.83 \pm 0.23 M_\odot$ in local CVs (e.g., Zorotovic et al. 2011). In recent years, the X-ray spectral fitting method demonstrated its power in that it can directly measure the temperature of the shock-heated matter and imply the WD mass by assuming the strong shock condition (e.g., Frank et al. 2002) in mCVs:

$$T_{\text{max}} = \frac{3 \mu m_H G M}{8 k R}.$$  

(1)

In the above equation, $T_{\text{max}}$ is the shock temperature, $\mu$ is the mean molecular weight, $m_H$ is the mass of the H atom, $k$ is the Boltzmann constant, $G$ is the gravitational constant, $M$ and $R$ are the mass and radius of the WD, respectively. For nonmagnetic CVs, $T_{\text{max}}$ is half of that value because half of the gravitational energy has been dissipated in the accretion disk. With the additional $M_{\text{WD}}-R_{\text{WD}}$ relation of WDs (Nauenberg 1972),

$$R_{\text{WD}} = 7.8 \times 10^8 \left[ \left( \frac{1.44 M_\odot}{M_{\text{WD}}} \right)^{2/3} - \left( \frac{M_{\text{WD}}}{1.44 M_\odot} \right)^{2/3} \right]^{1/2},$$  

(2)

one can derive the WD mass through

$$T_{\text{max}} = \frac{3 \mu m_H G M_{\text{WD}}}{8 k} \left( 7.8 \times 10^8 \left[ \left( \frac{1.44 M_\odot}{M_{\text{WD}}} \right)^{2/3} - \left( \frac{M_{\text{WD}}}{1.44 M_\odot} \right)^{2/3} \right]^{1/2} \right)^{-1}. $$  

(3)

The above correlation has been tested in dozens of local mCVs by various works (e.g., Suleimanov et al. 2005; Yuasa et al. 2010). A recent one was done by Yuasa et al. (2010), where the authors found a mean WD mass of $0.88 \pm 0.25 M_\odot$ for local mCVs based on Suzaku observations.

On the other hand, the population properties of WDs in distant CVs remains unclear because neither optical nor X-ray observations could provide a CV sample with a distance of over several hundred parsecs. The Galactic diffuse X-ray background, on the other hand, provides a natural sample for such a study. Discovered more than 30 years ago, the Galactic
ridge/bulge X-ray emission (GR/BXE) spans across the Galactic ridge and bulge in the energy range of 2–10 keV (here we follow the definition of Nobukawa et al. 2016, who define the GBXE as regions of $|l| < 0.6$, $1^\circ < |b| < 3^\circ$). The 1Ms Chandra observations on the “Limiting Window” in the Galactic bulge suggested that the GBXE is dominated by discrete sources (Revnivtsev et al. 2009b). The majority of which were proposed to be IBs, with a minor contribution from active binaries (ABs, e.g., Revnivtsev et al. 2009b; Hong et al. 2012). Thus, the composite X-ray spectra of the GBXE contains information from all the CVs (and ABs) in the direction in which they are free from selection effects and form an unbiased CV sample. With the assumption of mCV dominating the GBXE, Yuasa et al. (2012) fitted the $E > 15$ keV spectra of GBXE with an IP model and showed that the average WD mass in CVs is $0.66^{+0.09}_{-0.07} M_\odot$, which is close to 0.5–0.60 $M_\odot$ from INTEGRAL observations (Krivonos et al. 2007; Turler et al. 2010).

However, these results are only marginally consistent, if not inconsistent at all, with optical measurements for local CVs (0.83 ± 0.23 $M_\odot$; Zorotovic et al. 2011) or those of the Galactic center (~0.9 $M_\odot$; Hailey et al. 2016). In the Galactic center, the CVs in the crowded stellar environment may have experienced dynamical interactions, which preferentially bring massive WDs into binaries, and thus increased the mean WD mass in CVs. But the 0.2 $M_\odot$ discrepancy between local and the GBXE CVs is still confusing. The $T_{\text{max}}$–$M_{\text{WD}}$ correlation has been tested in dozens of local mCVs and there is no reason why this correlation could not be applied to mCVs in the Galactic bulge. Recently, Xu et al. (2016) proposed that the GBXE in the Fe emission line range (6–8 keV) should be dominated by non-mCVs instead of mCVs. Similar conclusions were also drawn by Nobukawa et al. (2016) and Hailey et al. (2016) by comparing X-ray continuum of different sources and of the Galactic center. Thus, we should apply the $T_{\text{max}}$–$M_{\text{WD}}$ correlation of non-mCVs to GBXE spectra to make a reliable measurement of average WD mass. Moreover, the accreted matter may exhibit a series of weak shocks in the boundary layer (BL) of non-mCVs, and the $T_{\text{max}}$–$M_{\text{WD}}$ correlation may deviate significantly from the theoretical formula (Frank et al. 2002). Moreover, for a typical DNe with $T_{\text{max}} \lesssim 80$ keV, a higher shock temperature usually means that there will be more hydrogen-like Fe ions comparing to helium-like ones. Therefore, the flux ratio of the hydrogen-like Fe line to the helium-like Fe line ($I_{6.7}/I_{6.7}$), is also sensitive to the shock temperature. For example, Xu et al. (2016) concluded that $I_{6.7}/I_{6.7}$ increases with increasing $T_{\text{max}}$ for $T_{\text{max}} < 80$ keV by assuming a cooling flow emission model. In this work, we choose to first test the validity of the strong shock assumption based on the X-ray spectroscopy of local non-mCVs and build semi-empirical $T_{\text{max}}$–$M_{\text{WD}}$–$I_{6.7}/I_{6.7}$ correlations. Next, we apply these correlations to the GBXE and constrain the average $M_{\text{WD}}$ in the Galactic bulge. We use the Suzaku archived sample of non-mCVs in this work because Suzaku can provide both a relatively self-consistent sample of non-mCVs and well studied data of the GBXE (e.g., Yuasa et al. 2012; Nobukawa et al. 2016). Furthermore, the spectra generally cover 0.3–40 keV, which is suitable for reliable $T_{\text{max}}$ measurements.

The rest of the paper is organized as follows: In Section 2, we describe our sample and data analysis methods. We present our results in Section 3. In Section 4 we compare them with existing results and discuss the implications. Finally, in Section 5, we provide a short summary.

2. Observations and Data Reduction

The Suzaku X-ray Observatory contains two types of instruments: one is the X-ray Imaging Spectrometers (XIS, Koyama et al. 2007), the other is the Hard X-ray Detector (HXD, Takahashi et al. 2007). The XIS consists of four sensors: one is made of back-illuminated CCD (XIS-1), and the other three are made of front-illuminated CCDs (XIS-0, 2, 3). XIS-2 suffered catastrophic damage on 2006 November 9 and no useful data have been transferred since then.

We cross-correlate the Suzaku online archive1 with Ritter & Kolb’s (2003) CV catalog to search for publicly available observations. A total of 25 observations on 18 DNe were found. The basic information regarding observed sources is listed in Table 1. This sample is certainly not a complete one. Nevertheless, it could provide us with information regarding the shock temperatures of DNe. Previous works based on similar observations only included XIS data (e.g., Byckling et al. 2010; Wada et al. 2017), but the best-fitted $T_{\text{max}}$ is usually above 10 keV; thus, HXD may be needed to put tighter constraints on $T_{\text{max}}$. We include both XIS and HXD data in this work.

The data processing and spectral analysis are carried out using HEASOFT2 (version 6.17, Arnaud 1996). The event files are reduced with the standard pipeline addascaspec tool to combine the spectra and response files of XIS-0, XIS-2 (if it exists), and XIS-3. We regroup the spectra so that the signal-to-noise ratio of each spectrum exceeds three. For HXD data, background files were downloaded from the Suzaku background FTP server3 and data were processed using the addxipsb tool. Due to the low net counts of HXD for most sources, the HXD spectra were grouped so that there were two to three bins at least.

3. Results

3.1. X-Ray Spectroscopy of Quiescent DNe

The X-ray spectra of quiescent DNe could be well fitted with the $mkCflow$ model in Xspec ( Mushotzky & Szymkowiak 1988; Mukai et al. 2003). We choose combined energy ranges of 0.3–10.0 keV for XIS and 12.0–50.0 keV for HXD (if it exists). We started by fitting the background-subtracted spectra with the model $phabs \times (mkCflow + Gaussian)$, or $phabs \times pcfabs \times (mkCflow + Gaussian)$ if additional intrinsic absorption is needed (see, e.g., Byckling et al. 2010; Wada et al. 2017), where $phabs$, $pcfabs$, $mkCflow$, and $Gaussian$ components account for the interstellar foreground absorption, the intrinsic absorption, the emission from the shock-heated plasma, and the Fe Ⅰ–Ⅴ fluorescent line, respectively. Examples of the best-fitting are plotted in Figure 1, and the results of $T_{\text{max}}$ are listed in Table 2.

1. ftp://heasarc.gsfc.nasa.gov/W3Browse/suzaku/suzamaster.html
2. https://heasarc.gsfc.nasa.gov/docs/software/heasoft/
3. ftp://legacy.gsfc.nasa.gov/suzaku/data/background
Table 1
Sampled DNe Properties

| Source      | Obs ID       | Exposure (ks) | Time (pc) | Distance (pc) | $M_{\text{WD}}$ (M$_{\odot}$) | Reference |
|-------------|--------------|---------------|-----------|---------------|--------------------------------|-----------|
| SS Cyg1     | 109015010*   | 43.2          | 117.1 ± 6.2 | 1.1 ± 0.2     | Ramsay et al. (2017), Friend et al. (1990) |
| SS Cyg2     | 400006010    | 39.5          | 117.1 ± 6.2 | 1.1 ± 0.2     | Ramsay et al. (2017), Friend et al. (1990) |
| SS Cyg3*    | 400007010*   | 56.0          | 117.1 ± 6.2 | 1.1 ± 0.2     | Ramsay et al. (2017), Friend et al. (1990) |
| V893 Sco    | 401041010    | 18.5          | 135 ± 66.5  | 0.89 ± 0.15c  | Ozdonmez et al. (2015), Mason et al. (2001) |
| VY Aqr      | 402043010    | 25.4          | 89 ± 13.10  | ...           | Ozdonmez et al. (2015) |
| SW UMa      | 402044010    | 16.9          | 159 ± 22    | 0.71 ± 0.22   | Gansicke et al. (2005), Ritter & Kolb (2003) |
| SS Aur      | 402045010    | 19.5          | 167 ± 9     | 1.08 ± 0.4    | Ozdonmez et al. (2015), Sion et al. (2008) |
| BZ UMa      | 402046010    | 29.7          | 204 ± 77    | 0.65 ± 0.15c  | Ozdonmez et al. (2015), Jurcevic et al. (1994) |
| FL Psc      | 403039010    | 33.3          | 160 ± 40    | ...           | Patterson (2011) |
| KT Per      | 403041010*   | 29.2          | 145 ± 31    | ...           | Ozdonmez et al. (2015) |
| GK Per      | 403081010    | 30.4          | 477 ± 28    | 0.87 ± 0.24   | Harrison et al. (2013), Morales-Rueda et al. (2002) |
| Z Cam1      | 404022010*   | 37.7          | 219.3 ± 19.5| 0.99 ± 0.15   | Ramsay et al. (2017), Ritter & Kolb (2003) |
| Z Cam2      | 407016010*   | 35.9          | 219.3 ± 19.5| 0.99 ± 0.15   | Ramsay et al. (2017), Ritter & Kolb (2003) |
| VW Hy1i     | 406009010*   | 70.1          | 46 ± 6      | 0.67 ± 0.22   | Ozdonmez et al. (2015), Hamilton et al. (2011) |
| VW Hy1v     | 406009020    | 16.2          | 46 ± 6      | 0.67 ± 0.22   | Ozdonmez et al. (2015), Hamilton et al. (2011) |
| VW Hy1v     | 406009030    | 20.1          | 46 ± 6      | 0.67 ± 0.22   | Ozdonmez et al. (2015), Hamilton et al. (2011) |
| VW Hy1v     | 406009040*   | 16.8          | 46 ± 6      | 0.67 ± 0.22   | Ozdonmez et al. (2015), Hamilton et al. (2011) |
| U Gem1      | 407034010    | 119.1         | 100 ± 4     | 1.2 ± 0.05    | Ozdonmez et al. (2015), Ritter & Kolb (2003) |
| U Gem2      | 407035010*   | 50.3          | 100 ± 4     | 1.2 ± 0.05    | Ozdonmez et al. (2015), Ritter & Kolb (2003) |
| CH UMa      | 407043010    | 45.2          | 356 ± 47    | 1.95 ± 0.3    | Ozdonmez et al. (2015), Friend et al. (1990) |
| EK Tra      | 407044010    | 77.8          | 180         | 0.46 ± 0.1    | Gansicke et al. (1997), Menneken & Arenas (1998) |
| BF Eri      | 407045010    | 32.8          | 596 ± 79    | 1.28 ± 0.05   | Ozdonmez et al. (2015), Neustroev & Zharikov (2008) |
| BV Cen      | 407047010    | 33.4          | 344 ± 68    | 1.24 ± 0.22   | Ramsay et al. (2017), Watson et al. (2007) |
| V1159 Ori   | 408029010    | 200.5         | 299         | ...           | Ak et al. (2008) |
| FS Aur      | 408041010    | 62.2          | 246 ± 32    | ...           | Ozdonmez et al. (2015) |

Notes. The state is determined using the American Association of Variable Star Observers (AAVSO) International Database.
* No HXD spectrum.
* Outburst state.
* 0.15 $M_\odot$ mass error assumed.
* Transitional state.
* Very low HXD net counts, HXD data is not used.

The last column of Table 2 shows the flux ratio of Fe XXVI–Lyα and Fe XXV–Heα lines from Xu et al. (2016).

3.2. The Empirical $M_{\text{WD}}$–$T_{\text{max}}$–$I_{7.0/6.7}$ Correlations for DNe

To build a $M_{\text{WD}}$–$T_{\text{max}}$ correlation for DNe, we exclude several sources that do not belong to the DNe class. For example, GK Per was proposed to be an IP with DN-like outbursts (see, e.g., Kim et al. 1992), BF Eri was proposed to be an old nova exhibiting “stunted” outbursts (Neustroev & Zharikov 2008). In addition, only quiescent DNe are included in the following analysis because the $T_{\text{max}}$ in other states would be different from that in the quiescent state due to the altering of the structure of the accretion disk and BL in high accretion rates (Wada et al. 2017). Furthermore, the Obs-ID 109015010 of SS Cyg did not include HXD data, so we only use the results from Obs-ID 400006010 to represent $T_{\text{max}}$ of SS Cyg. The data points of excluded sources are still plotted in the figures only for reference.

The masses of WDs in sampled DNe are adopted from various works, as listed in Table 1 (see references therein for details). We assign a typical 0.15 $M_\odot$ uncertainty to WD masses of V893 Sco and BZ UMa because the mass errors were not mentioned in the references (this assumption would not affect our results, see Section 4 for details). We further exclude CH UMa from our sample because its mass is higher than the Chandrasekhar limit. At last, we have 11 available data points from nine sources. In Figure 2, we plot $T_{\text{max}}$ against the WD mass with a theoretical green curve representing the strong shock condition case. It is obvious that the green curve deviates from the data points. We then simply assume a parameter $\alpha$, so that $T_{\text{max}}$ follows

$$T_{\text{max}} = \alpha \times \frac{3 \mu m_{\text{H}} GM}{16 k R}.$$  

where $\mu = 0.6$ is assumed. The best-fit results show an $\alpha = 0.646 \pm 0.069$, with $\chi^2(\text{DOF}) = 2.02(10)$ and an $r^2$ value of 0.69. The fitted curve with error ranges is given as a solid and dashed black curves in Figure 2.

As discussed in Xu et al. (2016), $I_{7.0}/I_{6.7}$, the flux ratio of H-like Fe to He-like Fe lines, is a good indicator of $T_{\text{max}}$ when $T_{\text{max}}$ is below ~50 keV. Thus $I_{7.0}/I_{6.7}$ is also correlated to the WD mass in CVs. In Figures 3 and 4, we plot the measured $I_{7.0}/I_{6.7}$ against $T_{\text{max}}$ and $M_{\text{WD}}$. In addition, we simulate the theoretical $I_{7.0}/I_{6.7}$ against $T_{\text{max}}$ and $I_{7.0}/I_{6.7}$–$M_{\text{WD}}$ (where $M_{\text{WD}}$ is converted to $T_{\text{max}}$ using Equation (4), uncertainty of $\alpha$ has been considered) correlation curves for solar and 0.1 solar metallicities from the mkclflow model. The resulting curves are also plotted in the figures. The data points, in general, are consistent with the semi-empirical correlation curves, except for three sources with low net counts (BF Eri, FL Psc, and VY Aqr) and two sources in the transition state (KT Per and Z Cam). In Table 2, we also list the $M_{\text{WD}}$ derived...
from the $I_{7.0}/I_{6.7} - M_{\text{WD}}$ correlation. In general, the derived WD masses of sampled DNe are all consistent with optical measurements (see Table 1 for details, BF Eri and GK Per are not included for comparison since they are not DNe).

We then conclude that DNe in the quiescent state have $I_{7.0}/I_{6.7} - T_{\text{max}}$ and $I_{7.0}/I_{6.7} - M_{\text{WD}}$ correlations, which are consistent with theoretical predictions. Moreover, the differences among different abundances is negligible when $T_{\text{max}}$ is less than $\sim 15$ keV.

4. Discussion

4.1. Comparison with Previous Measurements and Bias Estimation

Both Wada et al. (2017) and Byckling et al. (2010) have analyzed some of our sampled observations in their works. We then compare our best-fitting $T_{\text{max}}$ with theirs in Table 2. It is obvious that most of our results are consistent with theirs, which gives us confidence to make further investigations. The
Table 2
Best-fit $T_{\text{max}}$ and Comparison with Previous Works

| Source | Id     | $T_{\text{max}}$(keV) | $\chi^2$(DOF) | Model | $T_{\text{max}}$(keV) | $I_{1/0}/I_{0.7}$ | $M_{\text{WD}}$(M$_\odot$) |
|--------|--------|------------------------|---------------|-------|------------------------|-------------------|---------------------------|
| SS Cyg| 400006010 | 42.1^{+1.0}_{-1.0}  | 1.09(4513)    | 1     | 55.5^{+1.1}_{-0.7}  | 41.99^{+1.30}_{-0.76} | ...                      |
| V893 Sco | 401041010 | 15.7^{+1.1}_{-1.0}  | 0.91(2767)    | 2     | 14.9^{+1.1}_{-0.6}  | 19.3^{+1.40}_{-1.29}  | 0.37^{+0.06}_{-0.06}  | 0.84^{+0.13}_{-0.11}  |
| VY Aqr | 402043010 | 18.9^{+0.8}_{-0.9}  | 0.93(502)     | 1     | 18.4^{+1.2}_{-1.2}  | 16.4^{+1.12}_{-1.32}  | 0.9^{+0.01}_{-0.01}  | ...                      |
| SW UMa | 402044010 | 7.8^{+0.6}_{-0.5}   | 0.94(658)     | 1     | 7.5^{+0.4}_{-0.3}   | 8.3^{+0.62}_{-0.61}   | ...                      |
| SS Aur | 402045010 | 26.3^{+2.9}_{-2.9}  | 0.91(919)     | 1     | 26.5^{+2.1}_{-2.1}  | 23.4^{+1.02}_{-0.91}  | 0.56^{+0.14}_{-0.13} | 1.03^{+0.23}_{-0.23}  |
| BZ UMa | 402046010 | 13.6^{+0.9}_{-0.9}  | 1.00(1186)    | 1     | 13.7^{+0.4}_{-0.4}  | 13.7^{+0.81}_{-0.81}  | 0.40^{+0.17}_{-0.16} | 0.87^{+0.23}_{-0.23}  |
| FL Psc | 403090100 | 17.2^{+2.6}_{-2.4}  | 0.99(144)     | 1     | 15.0^{+1.7}_{-1.5}  | 14.4^{+3.06}_{-2.69}  | 0.10^{+0.57}_{-0.57} | < 1.20                   |
| KT Per | 403041010 | 13.8^{+1.5}_{-1.5}  | 0.92(1146)    | 1     | 14.5^{+0.5}_{-0.5}  | ...                  | 0.10^{+0.18}_{-0.18} | < 0.80                   |
| GK Per | 403081010 | 62.0^{+4.4}_{-4.4}  | 0.94(1681)    | 2     | ...                  | ...                  | 0.94^{+0.43}_{-0.43} | > 0.90                   |
| Z Cam | 404022010 | 25.7^{+1.4}_{-1.0}  | 1.10(3864)    | 2     | 27.6^{+0.5}_{-0.5}  | 25.7^{+2.16}_{-2.39}  | 0.58^{+0.05}_{-0.05} | 1.05^{+0.10}_{-0.11}  |
| VW Hyi1 | 406009020 | 8.7^{+0.2}_{-0.2}   | 1.06(1518)    | 1     | 9.3^{+0.1}_{-0.1}   | ...                  | 0.04^{+0.05}_{-0.05} | < 0.55                   |
| VW Hyi2 | 406009030 | 9.7^{+0.4}_{-0.6}   | 1.01(1524)    | 1     | 10.0^{+0.1}_{-0.1}  | ...                  | 0.21^{+0.06}_{-0.06} | 0.66^{+0.14}_{-0.12}  |
| VW Hyi3 | 406009040 | 9.2^{+0.5}_{-0.7}   | 0.98(1441)    | 1     | 9.8^{+0.1}_{-0.1}   | ...                  | 0.19^{+0.08}_{-0.08} | 0.63^{+0.15}_{-0.13}  |
| U Gem | 407034010 | 26.9^{+0.6}_{-0.7}  | 1.07(3387)    | 1     | 26.2^{+1.0}_{-1.0}  | 25.8^{+2.18}_{-2.43}  | 0.68^{+0.08}_{-0.08} | 1.13^{+0.12}_{-0.14}  |
| CH UMa | 407043010 | 14.3^{+0.7}_{-0.7}  | 0.99(1697)    | 1     | 15.0^{+0.7}_{-0.7}  | ...                  | ...                      | ...                     |
| EK Tra | 407044010 | 10.4^{+0.5}_{-0.4}  | 1.07(2425)    | 1     | 12.4^{+0.1}_{-0.2}  | ...                  | 0.16^{+0.08}_{-0.08} | 0.60^{+0.15}_{-0.14}  |
| BF Eri | 407045010 | 7.1^{+0.5}_{-0.5}   | 0.99(697)     | 1     | 10.2^{+0.9}_{-0.4}  | 8.7^{+0.54}_{-0.31}   | 0.53^{+0.09}_{-0.08} | 1.00^{+0.15}_{-0.14}  |
| BV Cen | 407047010 | 25.1^{+2.3}_{-2.4}  | 1.04(2866)    | 2     | 27.5^{+0.7}_{-0.7}  | ...                  | 0.53^{+0.06}_{-0.06} | 0.84^{+0.13}_{-0.11}  |
| V1159 Ori | 408020910 | 9.2^{+0.4}_{-0.4}   | 1.01(1855)    | 1     | ...                  | ...                  | 0.37^{+0.06}_{-0.06} | 0.84^{+0.13}_{-0.11}  |
| FS Aur | 408041010 | 21.1^{+1.7}_{-1.0}  | 0.96(1703)    | 1     | ...                  | ...                  | ...                      | ...                     |

Notes. Model 1: `phabs(mkchfow + Gaussian)`. Model 2: `phabs(pecfabs(mkchfow + Gaussian))`. Errors show a 90% confidence level.

a This work, errors show a 90% confidence level.

b Results of Wada et al. (2017), errors are one standard deviation.

c Results of Byckling et al. (2010), errors show a 90% confidence level.

d $I_{1/0}/I_{0.7}$ refers to Xu et al. (2016).

e $M_{\text{WD}}$ derived from $I_{1/0}/I_{0.7}$ using Equation (4).

f An energy band of >16 keV for HXD is used.

Figure 2. $T_{\text{max}}$–$M_{\text{WD}}$ correlation. Black points represent normal quiescent DNe. Red points are sources whose mass errors are assumed to be 0.15 M$_\odot$. Sources in the transition state are plotted with blue points. Only black and red data points are used for fitting. The solid green curve shows the theoretical $T_{\text{max}}$–$M_{\text{WD}}$ in the strong shock assumption. The solid and dashed black curves show the best-fitted $T_{\text{max}}$–$M_{\text{WD}}$ correlation and its error range.
Figure 3. $T_{\text{max}}$–$I_{7.0}/I_{6.7}$ correlation. The red and green curves show the theoretical correlation from the mkcflow model for solar and 0.1 solar metallicity, respectively. The data points are shown in black, blue, and cyan, using $T_{\text{max}}$ in this work and $I_{7.0}/I_{6.7}$ in Xu et al. (2016). Points in black, blue, and cyan are the sources in the quiescent state, the sources in the transition state, and sources with relatively low net photon counts, respectively.

Figure 4. $I_{7.0}/I_{6.7}$–$M_{\text{WD}}$ correlation. The curves show the semi-empirical correlation derived from Equation (4) and the $T_{\text{max}}$–$I_{7.0}/I_{6.7}$ theoretical correlation. The red and green curves correspond to 1 and 0.1 solar abundances, respectively. Normal DNe are plotted by black data points. Sources with assumed 0.15 $M_{\odot}$ WD mass error are plotted in red points. The source in the transition state is plotted as the blue point. Points in cyan show that sources have a relatively low net photon counts.
only exception is SS Cyg. Our \( T_{\text{max}} \) (42.1 ± 1.0 keV) is consistent with that of Byckling et al. (2010) but is about 10 keV lower than that of Wada et al. (2017). We suspect the difference may be due to the additional HXD data included in our analysis, because SS Cyg has a \( T_{\text{max}} \) much higher than 10 keV and should be better constrained by HXD data (see Figure 1).

Byckling et al. (2010) have suggested that the correlation between \( T_{\text{max}} \) and \( M_{\text{WD}} \) in DNe is consistent with the strong shock assumption, equivalent to \( \alpha = 1 \) in Equation (4). However, our best-fitting results suggest \( \alpha = 0.646 \pm 0.069 \). This discrepancy could be due to the different sampled DNe in their work. For example, BV Cen and U Gem are included in this work but not in theirs. These two sources are essential in our analysis because they provide important data points of relatively massive WDs, which could alter the fitting results significantly. Furthermore, Byckling et al. (2010) only plotted the theoretical curve and did not provide a fitting, which may also affect their arguments.

The potential biases in our fitting mostly come from the uncertainties brought by the optical/UV mass measurements and the limited sample size. As shown in Table 1, the typical WD mass error is on the order of \( \sim 0.1-0.2 M_\odot \). This error is equivalent to a \( T_{\text{max}} \) uncertainty of \( \sim 8-20 \) keV, which is much greater than the typical \( T_{\text{max}} \) error of \( \sim 1 \) keV in this work. On the other hand, only 9 out of 18 X-ray sampled DNe have mass measurements, which greatly limits our sample size and could add more uncertainties to our results. Thus, to test and improve the \( T_{\text{max}}-M_{\text{WD}} \) correlation in the future, we need better constrained WD mass values of more CVs. Furthermore, there are multiple WD mass results for several sources, including SS Cyg and BZ UMa. For example, the WD mass in SS Cyg was measured to be \( 0.81 \pm 0.20 M_\odot \), \( 1.09 \pm 0.19 M_\odot \), and \( 1.19 \pm 0.02 M_\odot \) by various authors (e.g., Friend et al. 1990; Bitner et al. 2007). We tested each of them in the fitting, and found that the \( T_{\text{max}}-M_{\text{WD}} \) correlation was altered by \( \sim 10\% \), with a \( \alpha \) value from 0.58 to 0.65, respectively. We also tested the effects of excluding sources with assumed mass errors by removing data points of BZ UMa and V893 Sco, and performed fitting again. The new best-fitted \( \alpha \) value is 0.63 ± 0.08, which is within 5\% of the original value. These changes in \( \alpha \) would alter the resulting mean \( M_{\text{WD}} \) (see Section 4.2) in a \( \sim 5\% \) level, so we will use \( \alpha = 0.646 \pm 0.069 \) to make further discussion.

4.2. Average Mass of WDs in DNe in the Galactic Bulge

To imply the mean WD mass in the GBXE CVs, we need a reliable measurement of \( T_{\text{max}} \). However, the traditional method of deriving \( T_{\text{max}} \) by X-ray continuum fitting involves a major complication in the GBXE case. The GBXE continuum is a composition of multiple classes of sources (e.g., mCVs, non-mCVs, and ABs, Revnivtsev et al. 2009b), and it is difficult to quantify the contribution of DNe alone. For example, in the energy range above 10–15 keV, the GBXE would be a mixture of both mCV and non-mCV emissions; in the energy range below 2–4 keV, emission from ABs could be important (e.g., Nobukawa et al. 2016; Xu et al. 2016). Thus neither the hard X-ray band nor the broadband spectroscopy could give a reliable measurement of DNe \( T_{\text{max}} \). On the other hand, in the energy range containing He- and H-like Fe lines (6–8 keV), the GBXE spectra should be dominated by DNe (Xu et al. 2016). So we can make use of the Fe line flux ratio \( I_{\alpha}/I_{\beta} \) as an indicator of DNe \( T_{\text{max}} \), and imply \( M_{\text{WD}} \) directly. To do so, we adopt the GBXE Fe line ratio value of \( I_{\alpha}/I_{\beta} = 0.34 \pm 0.02 \) from Nobukawa et al. (2016). This value, according to the semi-empirical curves in Figures 3 and 4, corresponds to a temperature of \( T_{\text{max}} = 12 \pm 0.6 \) keV and a mean WD mass of \( \langle M_{\text{WD}} \rangle = 0.81 \pm 0.07 M_\odot \), respectively. This result is consistent with local value of \( 0.83 \pm 0.23 M_\odot \) by Zorotovic et al. (2011).

The above measurement of \( M_{\text{WD}} \) depends sensitively on the precise \( I_{\alpha}/I_{\beta} \) value of DNe in GBXE. Recently, Nobukawa et al. (2016) concluded that, in the energy range of 5–10 keV, the flux percentage of mCVs, non-mCVs, and ABs in GBXE are \( \sim 3\% \), \( 67\% \pm 6\% \), and \( 30\% \pm 3\% \), respectively. Thus, the contribution of Fe lines from mCVs could be ignored. The contribution of Fe lines from ABs, on the other hand, should be considered. Although a quantitative investigation of Fe XXV–He\( \alpha \) properties of ABs combined with their luminosity function is beyond the scope of this work, we could give a qualitative analysis as follows. In general, ABs have relatively lower \( T_{\text{max}} \), thus they emit more Fe XXV–He\( \alpha \) photons and less Fe XXVI–Ly\( \alpha \) photons compared to DNe, so the existence of ABs will reduce the \( I_{\alpha}/I_{\beta} \) value of GBXE. In another words, the real \( I_{\alpha}/I_{\beta} \) of DNe in GBXE should be higher than the measured GBXE value (0.34 ± 0.02). As a result, our measured \( \langle M_{\text{WD}} \rangle = 0.81 \pm 0.07 M_\odot \) should be considered to be the lower limit of the average WD mass of DNe in the GBXE. This result is still consistent with Zorotovic et al. (2011).

Comparing to previous works of GBXE mean \( M_{\text{WD}} \), the mean WD mass of 0.81 ± 0.07 \( M_\odot \) is higher than Yuasa et al.’s (2012) GBXE result of \( \sim 0.66 M_\odot \). This discrepancy could be explained as follows: The Yuasa et al. (2012) work assumed an mCV origin of GBXE, and implied the mCV WD mass by \( >15 \) keV GBXE X-ray continuum fitting. As discussed above, the GBXE in this energy range should include a contribution from both mCVs and non-mCVs. Because non-mCVs usually have lower \( T_{\text{max}} \) than mCVs, Yuasa et al.’s (2012) fitting would result in a relatively lower \( T_{\text{max}} \), and therefore an \( M_{\text{WD}} \) lower than local mCVs (\( \sim 0.9 M_\odot \), Yuasa et al. 2010). Interestingly, directly applying the DNe \( T_{\text{max}}-M_{\text{WD}} \) correlation to the above hard X-ray continuum would instead overestimate the average WD mass to \( \sim 1.15 M_\odot \) (which is much higher than the local value), because such a method would ignore the contribution of mCVs. The continuum fitting method can give robust measurements of \( M_{\text{WD}} \) of local CVs, but for the GBXE, the contribution of various classes of sources must be quantified (e.g., a reliable luminosity function has to be built) before this method could be applied.

5. Summary

We have analyzed observations of DNe from Suzaku archives and presented an empirical formula of \( T_{\text{max}}-M_{\text{WD}} \) of DNe, which could help us estimate the WD mass of DNe in the quiescent state through X-ray observations. We also present the \( I_{\alpha}/I_{\beta}-T_{\text{max}} \) and \( I_{\alpha}/I_{\beta}-M_{\text{WD}} \) correlation of DNe, and imply the average WD mass of DNe in the Galactic bulge to be \( \langle M_{\text{WD}} \rangle = 0.81 \pm 0.07 M_\odot \). This result is consistent with measurements of local WDs in CVs.

The authors thank the anonymous referee for constructive comments that helped improve this paper. This work is supported by National Science Foundation of China through grants NSFC-11303015, the National Key Research and
Development Program of China (2016YFA0400803), NSFC-11773015, NSFC-11133001, and NSFC-11333004.

ORCID iDs
Xiao-jie Xu © https://orcid.org/0000-0002-3614-1070

References
Ak, T., Bilir, S., Ak, S., & Eker, Z. 2008, NewA, 13, 133
Arnaud, K. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Bitter, M. A., Robinson, E. L., & Behr, B. B. 2007, ApJ, 662, 564
Byckling, K., Mukai, K., Thorstensen, J. R., & Osborne, J. P. 2010, MNRAS, 408, 2298
Frank, J., King, A., & Raine, D. 2002, Accretion Power in Astrophysics (Cambridge: Cambridge Univ. Press)
Friend, M. T., Martin, J. S., Connolly-Smith, R., & Jones, D. H. P. 1990, MNRAS, 246, 654
Gansicke, B. T., Beuermann, K., & Thomas, H. C. 1997, MNRAS, 289, 388
Gansicke, B. T., Szkody, P., Howell, S. B., & Sion, E. M. 2005, ApJ, 629, 451
Hailey, C. J., Mori, K., Perez, K., et al. 2016, ApJ, 826, 161
Hamilton, R. T., Harrison, T. E., Tappert, C., & Howell, S. B. 2011, ApJ, 728, 16
Harrison, T. E., Bornak, J., McArthur, B. E., & Benedict, G. F. 2013, ApJ, 767, 7
Hong, J., van den Berg, M., Grindlay, J. E., et al. 2012, ApJ, 746, 165
Jurcevic, J. S., Honeycutt, R. K., Schlegel, E. M., & Webbink, R. F. 1994, PASP, 106, 481
Kim, S.-W., Wheeler, J. C., & Mineshige, S. 1992, ApJ, 384, 269
Koyama, K., Tsunemi, H., Dotani, T., et al. 2007, PASJ, 59, 23
Krivonos, R., Revnivtsev, M., Charazov, E., et al. 2007, A&A, 463, 957
Liebert, J., Bergeron, P., & Holberg, J. B. 2003, AJ, 125, 348
Liu, W.-m., & Li, X.-d. 2016, ApJ, 832, 80
Mason, E., Skidmore, W., Howell, S. B., & Mennekent, R. E. 2001, ApJ, 563, 351
Mennekent, R. E., & Arenas, J. 1998, PASJ, 50, 333
Morales-Rueda, L., Still, M. D., Roche, P., Wood, J. H., & Lockley, J. J. 2002, MNRAS, 329, 597
Mukai, K., Kinkhabwala, A., Peterson, J. R., Kahn, S. M., & Paerels, F. 2003, ApJ, 586, L77
Mushotzky, R. F., & Szomski, A. E. 1988, in NATO ASIC Proc. 229:
Cooling Flows in Clusters and Galaxies, ed. A. C. Fabian (Dordrecht: Kluwer Academic Publishers), 53
Nauenberg, Michael 1972, ApJ, 175, 417
Neustroev, V. V., & Zharikov, S. 2008, MNRAS, 386, 1366
Nobukawa, M., Uchiyama, H., Nobukawa, K. K., Yamauchi, S., & Koyama, K. 2016, ApJ, 833, 268
Ozdonmez, A., Ak, T., & Bilir, S. 2015, NewA, 34, 2340
Patterson, J. 2011, MNRAS, 411, 2695
Preotoius, M. L., Knigge, C., & Schwpe, A. D. 2013, MNRAS, 432, 570
Prialnik, D., & Kovetz, A. 1995, ApJ, 445, 789
Ramsay, G., Schreiber, M. R., Gansicke, B. T., & Wheatley, P. J. 2017, A&A, 604, 107
Revnivtsev, M., Sazonov, S., Charazov, E., et al. 2009a, Natur, 458, 1142
Revnivtsev, M., Sazonov, S., Charazov, E., et al. 2009b, NewA, 458, 1142
Ritter, H., & Kolb, U. 2003, A&A, 404, 301
Sazonov, S., revnivtsev, M., Gilfanov, M., et al. 2006, A&A, 450, 117
Sion, E. M., Gansicke, B. T., Long, K. S., et al. 2008, ApJ, 681, 543
Suleimanov, V., Revnivtsev, M., & Ritter, H. 2005, A&A, 435, 191
Takahashi, T., Abe, K., Endo, M., et al. 2007, PASJ, 59, 35
Turler, M., Chernyakova, M., Courvoisier, T., et al. 2010, A&A, 512, 49
Wada, Q., Tsujimoto, M., Ebisawa, K., & Hayashi, T. 2017, PASJ, 69, 10
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ. Press)
Warwick, R. S. 2014, MNRAS, 445, 66
Watson, C. A., Steeghs, D., Shahbaz, T., & Dhillon, V. S. 2007, MNRAS, 382, 1105
Xu, X.-J., Daniel Wang, Q., & Li, X.-D. 2016, ApJ, 818, 136
Yaron, O., Prlhalnik, D., Shara, M. M., & Kovetz, A. 2005, ApJ, 623, 398
Yuasa, T., Makishima, K., & Nakazawa, K. 2012, ApJ, 753, 129
Yuasa, T., Nakazawa, K., Makishima, K., et al. 2010, A&A, 520, 25
Zorotovic, M., Schreiber, M. R., & Gansicke, B. T. 2011, A&A, 536A, 42