Massive White Dwarfs in the Galactic Center: A Chandra X-Ray Spectroscopy of Cataclysmic Variables

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Abstract

Previous X-ray observations toward the nuclear star cluster (NSC) at the Galactic center have discovered thousands of point sources, most of which were believed to be cataclysmic variables (CVs), i.e., a white dwarf (WD) accreting from a low-mass companion. However, the population properties of these CVs remain unclear, which otherwise would provide important information about the evolutionary history of the NSC. In this work we utilize ultra-deep archival Chandra observations to study the spectral properties of the NSC CVs, in close comparison with those in the solar vicinity. We find that the NSC CVs have strong Fe XXV and Fe XXVI lines (both of which show equivalent widths \( \sim 200-300 \) eV), indicating metal-rich companions. Moreover, their Fe XXVI to Fe XXV line flux ratio is used to diagnose the characteristic WD mass (\( M_{\text{WD}} \)) of NSC CVs. The results show that the CVs with \( L_{2-10\ \text{keV}} > 6 \times 10^{31} \text{erg s}^{-1} \) have a mean \( M_{\text{WD}} \) of \( \sim 0.6/1.0 \text{M}_\odot \), if they are magnetic/nonmagnetic CVs; while those with \( L_{2-10\ \text{keV}} \) between 1 and \( 6 \times 10^{31} \text{erg s}^{-1} \) have a mean \( M_{\text{WD}} \) of \( \sim 0.8/1.2 \text{M}_\odot \), if they are magnetic/nonmagnetic CVs. All these Chandra detected CVs collectively contribute \( \sim 30\%-50\% \) of the unresolved 20–40 keV X-ray emission from the NSC. The CV population with massive (i.e., \( M_{\text{WD}} \sim 1.2 \text{M}_\odot \)) WDs have not been observed in the solar vicinity or the Galactic bulge, and they might have been formed via dynamical encounters in the NSC.

Key words: binaries: close – Galaxy: center – stars: kinematics and dynamics – X-rays: binaries

1. Introduction

Consisting of a vast number (\( \sim 10^7 \)) of predominantly old stars densely concentrated in the innermost few parsecs of our Galaxy, the nuclear star cluster (NSC) provides an important laboratory for the understanding of fundamental astrophysics (see Genzel et al. 2010 for a recent review). In particular, how individual stars and binaries would evolve under the influence of their mutual dynamics, which is persistently regulated by the gravity of a central supermassive black hole (SMBH).

In this work, we concentrate on the population properties of cataclysmic variables (CVs), in which a white dwarf (WD) accretes matter from its main-sequence or sub-giant companion star and emits X-rays. CVs are good targets to study the stellar evolution theory, and they are closely related to more interesting astrophysical objects, like the progenitors of type Ia supernovae, which are believed to be binaries containing one or two WDs (Wang & Han 2012), and close double WD binaries, which are main targets for future gravitational wave detectors like TianQin (Luo et al. 2016).

In the past two decades, X-ray observations have provided an important approach to study the CV in the NSC. X-ray photons from CVs with energy above \( \sim 2 \) keV can penetrate the foreground absorbing gas and provide information on the binary population and therefore the changes due to dynamical effects in the NSC. For example, the specific X-ray luminosity function of point sources (normalized by total stellar mass) in the NSC region shows the enhanced abundance of X-ray sources above \( \sim 10^{31} \text{erg s}^{-1} \) (e.g., Muno et al. 2009; Zhu et al. 2018), compared to those in the field. The combined X-ray spectra of point sources in the GC region resemble those of CVs in the solar vicinity, suggesting that the origin of these sources should be CVs, just like the Galactic bulge/ridge X-ray emission (GB/RXE; Muno et al. 2003, 2009; Sazonov et al. 2006; Revnivtsev et al. 2009; Zhu et al. 2018). Moreover, recent NuSTAR observations have revealed an extended 20–40 keV hard X-ray emission in the NSC field, which was named central hard X-ray emission (CHXE; Perez et al. 2015; Hailey et al. 2016) in comparison to the well known Galactic center X-ray emission (GCXE). The broadband 2–40 keV spectrum of CHXE is consistent with spectra of magnetic CVs (mCVs, including polars and intermediate polars, aka, IPs) in the solar vicinity (Hailey et al. 2016). The average shock temperature (\( T_{\text{max}} \)) and mass of the WDs (\( M_{\text{WD}} \)) were constrained to be \( \sim 40 \text{keV} \) and \( \sim 0.9 \text{M}_\odot \), respectively. Based on the luminosity function of point sources detected by previous Chandra observations in the same region, Hailey et al. (2016) further proposed that several thousands of mCVs, more specifically, IPs with 2–10 keV luminosity down to \( \sim 5 \times 10^{31} \text{erg s}^{-1} \) would explain the CHXE.

Using a total of 4.4 Ms Chandra observations, Zhu et al. (2018) pushed the 2–10 keV detection limit to \( \sim 10^{31} \text{erg s}^{-1} \) (assuming a distance of 8 kpc) in the NSC. The point sources within 250" and \( L_X \) below \( 6.0 \times 10^{31} \text{erg s}^{-1} \) show strong H-like and He-like Fe emission lines (centered at \( \sim 6.97 \text{keV} \) and \( \sim 6.7 \text{keV} \), respectively), which is consistent with typical IPs. However, the luminosities of these Chandra detected sources are below the typical luminosity of magnetic CVs in the solar vicinity (\( \gtrsim 10^{32} \text{erg s}^{-1} \)). As a result, their exact origin and the mean WD mass remain to be explored.

The flux ratio of Fe XXVI to Fe XXV emission lines (\( I_{70}/I_{67} \)) can be taken as a sensitive diagnostic for \( T_{\text{max}} \) and \( M_{\text{WD}} \) for CVs (Xu et al. 2016, 2019; Yu et al. 2018, see also Section 3 for details). This is because a more massive WD would have a
higher $T_{\text{max}}$, thus more hydrogen-like Fe ions and a higher $I_{T,0}/I_{T,7}$. In this work, we use the $I_{T,0}/I_{T,7} - T_{\text{max}}$ relations examined by IPs and non-mCVs in the solar vicinity by Xu et al. (2019) to diagnose the CV populations in the NSC. We describe our data and method in Section 2. We compare the Fe line properties of the GCXE and the CHXE sources to those of CVs in solar vicinity in Section 3, we explore the CV population in the NSC in Section 4 and summarize in Section 5. Throughout this work, we quote errors at the 90\% confidence level, unless otherwise stated.

### 2. X-Ray Data and Analysis

Our data reduction procedure is as described in Zhu et al. (2018), which presents a catalog of more than 3500 X-ray sources located in the inner 20 pc region of the GC, based on ultra-deep *Chandra* observations taken with the Advanced CCD Imaging Spectrometer (ACIS). Since we are primarily interested in the spectral properties of CVs, other classes of X-ray sources in this catalog, e.g., X-ray transients (most likely LMXBs) and colliding wind massive binaries, as well as extended sources, have been excluded (see Zhu et al. 2018 for details of source identification). Any residual non-CV sources, in particular, quiescent low-mass X-ray binaries (qLMX Bs) that are typically devoid of significant Fe lines, were estimated to be $\lesssim 5\%$ in number and should not significantly affect our results.

We focus on the GCXE region, defined here as the half-circle with a projected galacto-centric radius $R = 250''$ and Galactic latitude $b > 0$, the latter criterion adopted to minimize the diffuse background (Figure 1). We then divide the point sources detected therein into two groups according to their luminosities: GCXE-H (GCXE-L) consists of sources having $2-10\text{ keV}$ unabsorbed luminosity above (below) $6 \times 10^{-3} \text{ erg s}^{-1}$, as measured in Zhu et al. (2018). Most IPs (non-mCVs) in the Solar vicinity are found above (below) this luminosity threshold (e.g., Xu et al. 2016). The H and L sources are further divided into three subgroups, according to their projected distances to Sgr A*: region I for $1'' < R < 100''$, region II for $100'' < R < 170''$, and region III for $170'' < R < 250''$. Finally, to compare with the *NuSTAR* results, we select those *Chandra* sources falling within the CHXE-SW region as defined in Perez et al. (2015). The spatial occupation of various subgroups are illustrated in Figure 1. For a given subgroup, we extract the cumulative spectra for each ObsID, using the CIAO tool *specextract*, and combine them with *combine_spectra*. While both ACIS-I and ACIS-S data were utilized by Zhu et al. (2018) for source detection, here we use only the 3 Ms ACIS-S data to ensure an optimal spectral resolution for the Fe lines (including obs-IDs of 13850, 14392, 14394, 14393, 13856, 13857, 13854, 14413, 13855, 14414, 13847, 14427, 13848, 13849, 13846, 14438, 13845, 14460, 13844, 14461, 13853, 13841, 14465, 14466, 13842, 13839, 13840, 14432, 13838, 13852, 14439, 14462, 14463, 13851, 15568, 13843, 15570, and 14468. See Zhu et al. (2018) for detailed reasoning). The number of sources in each subgroup ranges from 99 to 462, which is sufficiently large to ensure that none of the cumulative spectra is dominated by just a few sources.

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*Figure 1. Chandra 2–8 keV image of the 500'' × 500'' region centered at Sgr A*, from Xu et al. (2018). The blue polygon denotes the CHXE-SW region defined by Perez et al. (2015), the pink crosses denote the positions of the two brightest sources from Zhu et al.’s (2018) catalog, and the three orange half-annuli are regions I, II, and III, in order of increasing radius.*
Following Xu et al. (2016) and Zhu et al. (2018), the 3–8 keV continuum are then fitted with a phenomenological bremsstrahlung model. To account for the Fe lines, we make use of the 3-Gaussian model by Xu et al. (2016), which was specifically constructed for this purpose. The parameters of this model include the centroid energies, widths, and (relative) intensities ($I_{6.4}/I_{6.7}$, $I_{6.7}$, and $I_{7.0}/I_{6.7}$) of the lines. This model automatically accounts for the correlations between the parameters of the Fe lines in error measurements, which can effectively reduce the error ranges of $I_{7.0}/I_{6.7}$ for further comparison. Both of the above components are subject to an absorption column of order $10^{23}$ cm$^{-2}$ (including foreground and intrinsic partial absorption).

The GCXE-H, GCXE-L, and CHXE spectra are shown in the top panel of Figure 2. Equivalent widths (EWs) and line flux ratios are derived from the spectral fit and presented in Table 1. It can be seen that the EW of Fe XXVI (EW$_{6.7}$), EW of Fe XXV (EW$_{6.7}$), and Fe XXVI to Fe XXV line flux ratio ($I_{7.0}/I_{6.7}$) are systematically higher in the L sources than in the H sources. On the other hand, the $I_{7.0}/I_{6.7}$ values are consistent to within uncertainties among regions I, II, and III; a similar conclusion can be drawn for the EWs (EW$_{7.0}$ of region III is marginally higher than the other two regions for the H sources). Therefore, we conclude that there is no significant radial gradient in the line ratio or EWs, and will not further distinguish these three subgroups.

Figure 2. Cumulative Chandra spectra of CHXE (black), GCXE-H (red) and GCXE-L (green) sources. The spectra are fitted by an absorbed bremsstrahlung $+$ 3-Gaussian model to characterize the three Fe emission lines. The error bars are of 1σ.

Table 1

| Source | EW$_{6.4}$ (eV) | EW$_{6.7}$ (eV) | EW$_{7.0}$ (eV) | $I_{7.0/6.7}$ | $T_{\text{max}}^a$ (keV) | $M_{\text{WD}}^a$ (M$_{\odot}$) | $\chi^2$/dof |
|--------|----------------|----------------|----------------|---------------|----------------|----------------|-------------|
| CHXE   | 46$^{+24}_{-14}$ | 286$^{+100}_{-70}$ | 190$^{+28}_{-20}$ | 0.65 ± 0.20 | 23$^{+10}_{-8}$ | 0.61$^{+0.11}_{-0.14}$/0.17 | 0.72/95 |
| GCXE   | 61$^{+5}_{-10}$ | 297 ± 30 | 206$^{+30}_{-10}$ | 0.71 ± 0.06 | 26$^{+3}_{-2}$ | 0.65$^{+0.07}_{-0.09}$/1.11 | 0.79/268 |
| GCXE-H | 66 ± 7 | 269 ± 15 | 164 ± 15 | 0.60 ± 0.05 | 21$^{+3}_{-2}$ | 0.57$^{+0.02}_{-0.04}$/0.04 | 0.95/336 |
| GCXE-L | 41 ± 17 | 308 ± 32 | 310 ± 36 | 0.92 ± 0.13 | 38$^{+11}_{-10}$ | 0.83$^{+0.11}_{-0.15}$/1.25 | 0.72/250 |
| H$_{1}$ | 77 ± 26 | 207 ± 60 | 120 ± 30 | 0.56 ± 0.22 | ... | ... | 0.91/273 |
| H$_{II}$ | 73 ± 28 | 232 ± 45 | 110 ± 40 | 0.47 ± 0.17 | ... | ... | 1.1/272 |
| L$_{II}$ | 86 ± 29 | 221 ± 24 | 191 ± 30 | 0.76 ± 0.19 | ... | ... | 0.93/261 |
| L$_{III}$ | <44 | 580 ± 220 | 470 ± 190 | 1.0$^{+0.6}_{-0.4}$ | ... | ... | 1.3/11 |
| L$_{IV}$ | <42 | 370 ± 80 | 269 ± 87 | 0.71 ± 0.13 | ... | ... | 0.78/116 |
| L$_{III}$ | 77$^{+103}_{-34}$ | 262 ± 110 | 300$^{+110}_{-140}$ | 1.09 ± 0.4 | ... | ... | 0.87/98 |

Notes.

$a$ The $T_{\text{max}}$ and the $M_{\text{WD}}$ derived from the $I_{7.0/6.7}$ values using the $I_{7.0/6.7}$-$T_{\text{max}}$-$M_{\text{WD}}$ relations by Xu et al. (2019), see the text and Figure 3 for details.

$b$ Averaged value of IPs and non-mCVs in the solar vicinity (Xu et al. 2016).
3. Iron Line Diagnostics for CV Populations

3.1. Methodology

The maximum temperature ($T_{\text{max}}$) and the mass of WD ($M_{\text{WD}}$) in CVs can be related via $T_{\text{max}} = \frac{3 \mu \text{M}_{\text{WD}}}{8 \kappa r_{\text{WD}}}$ for IPs (e.g., Frank et al. 2002), and $T_{\text{max}} = \frac{3 \mu \text{M}_{\text{WD}}}{16 \kappa R_{\text{WD}}}$, where $\mu = 0.65 \pm 0.07$ for non-mCVs (Yu et al. 2018). However, Chandra spectra alone are not robust for the measurement of $T_{\text{max}}$ owing to the limited sensitivity of Chandra at energies above $\sim 8$ keV. Fortunately, the line ratio $L_{\text{Ly}\alpha}/L_{\text{He}\alpha}$ can be taken as a sensitive diagnostic for $T_{\text{max}}$. The $I_{\text{7.0}}/I_{67}$-$T_{\text{max}}$ and $I_{\text{7.0}}/I_{67}-M_{\text{WD}}$ relations have been built and examined in detail for 25 non-mCVs and IPs in the solar vicinity based on Suzaku and NuSTAR observations (e.g., Xu et al. 2016, 2019; Yu et al. 2018). Furthermore, the relation of non-mCVs has been applied to the Galactic bulge X-ray emission (GBXE) to constrain the mean WD mass in CVs ($\sim 0.8 M_\odot$, Yu et al. 2018).

To provide a useful diagnostic for the CV populations in the NSC, we incorporate the most recent $I_{\text{7.0}}/I_{67}$-$T_{\text{max}}$ and $I_{\text{7.0}}/I_{67}-M_{\text{WD}}$ relations by Xu et al. (2019), and plot them in Figure 3 as solid and dashed curves for $Z = 1$ and $Z = 0.1$ solar values, respectively. To constrain the metallicity of NSC CVs, we simulate a series of CV spectra using the rmf and arf files of the observed Chandra spectrum with metallicities ranging from 0.1 to 2 in solar value, assuming as input the mkcflow model (which is generally used to fit the CV spectra, see, e.g., Mukai 2017) with $T_{\text{max}} = 40$ keV, and 3–8 keV flux and the exposure time same as in the observed spectrum. We find that to reproduce the observed EWs of the GCXE spectrum, the simulated spectrum based on the mkcflow model requires a metallicity $Z > 0.6$ at the 90% confidence level. This is consistent with the expectation that the GC stellar populations are predominantly of a solar or even super-solar metallicity.

3.2. $M_{\text{WD}}$ of CVs in the NSC

As shown in Figure 2, the cumulative spectra of GCXE and CHXE sources show significant Fe lines, which represent the average line strengths of the constituent sources, presumably CVs. Furthermore, the luminosity function of the detected NSC sources can be described by $N(>L) \propto L^{-1.63\pm0.16}$ (Zhu et al. 2018). Such a steep luminosity function implies that the cumulative spectra represent the average properties of the majority of point sources, i.e., the less luminous CVs in the NSC. Therefore, we can employ the $I_{\text{7.0}}/I_{67}$-$T_{\text{max}}$-$M_{\text{WD}}$ relations in Section 3.1 to infer the characteristic shock temperature and mean WD mass of CVs in the NSC.

We take the relation with $Z = 1$ as fiducial, noting that the uncertainty associated with any reasonable range of metallicity in the NSC should be small compared to the statistical errors in the measured $I_{\text{7.0}}/I_{67}$ values.

From Table 1, the GCXE (i.e., the H+L) sources have $I_{\text{7.0}}/I_{67}$ of $0.71 \pm 0.06$, which is consistent with $I_{\text{7.0}}/I_{67} = 0.65 \pm 0.20$ of the CHXE sources. Both values are comparable to the mean $I_{\text{7.0}}/I_{67}$ of IPs in the solar vicinity ($0.71 \pm 0.04$, see Table 1 and Xu et al. 2016), but are significantly higher than the mean of non-mCVs in the solar vicinity ($0.27 \pm 0.06$). Using the $I_{\text{7.0}}/I_{67}$-$T_{\text{max}}$ relation in Figure 3, the average $T_{\text{max}}$ of H, L, GCXE and CHXE sources can be estimated as $21^{+3}_{-2}$ keV, $38^{+11}_{-9}$ keV, $26^{+3}_{-2}$ keV, and $23^{+3}_{-8}$ keV, respectively. Notably, $T_{\text{max}}$ of the L sources is comparable to the shock temperature of $43^{+11}_{-6}$ keV measured by NuSTAR (derived from the $M_{\text{WD}}$ measurements with IPM model by Hailey et al. 2016); $T_{\text{max}}$ of the H, GCXE and CHXE sources are consistent with each other, but lower than the NuSTAR measurement.

According to the $I_{\text{7.0}}/L_{67}$-$M_{\text{WD}}$ relation in Figure 3, the average $M_{\text{WD}}$ of the H, L, H + L, and CHXE sources can be constrained as $0.57^{+0.05}_{-0.02} M_\odot$, $0.83^{+0.11}_{-0.11} M_\odot$, $0.65^{+0.07}_{-0.02} M_\odot$, and $0.61^{+0.19}_{-0.1} M_\odot$ if they were mostly IPs, and $1.04^{+0.04}_{-0.02} M_\odot$, $1.25^{+0.07}_{-0.08} M_\odot$, $1.11^{+0.06}_{-0.03} M_\odot$, and $1.07^{+0.13}_{-0.16} M_\odot$ if they were predominately non-mCVs.

In the above analysis, we assume that the mean line ratio and its error can represent the typical range of the individual sources. To verify this assumption, we further inspect the spectra of the brightest individual sources. We extract and fit the cumulative spectra of two brightest sources (Source No.2338 and No.2942 in the NSC X-ray source catalog of Zhu et al. 2018, each having more than 1800 net counts in the combined ACIS-S data.) in the GCXE region with the same procedure. Both sources belong to the H group, and their J2000 coordinates are R.A. = 17:45:41.498, decl. = $-28:58:14.83$ for No.2338 and R.A. = 17:45:48.948, decl. = $-28:57:51.73$ for No.2942, respectively. The spectra and fitting results are presented in Figure 4 and Table 1. It can be seen that the spectra of No.2338 and No.2942 both show significant Fe lines and bremsstrahlung-like continuum, which are typical for CVs. The $I_{\text{7.0}}/I_{67}$ of No.2338 (0.30$^{+0.28}_{-0.17}$) is consistent with that of non-mCVs, and the $I_{\text{7.0}}/I_{67}$ of No.2942 (1.08$^{+0.46}_{-0.24}$) is consistent with that of IPs in the solar vicinity. We further examine the 2–8 keV light curve of the two sources, following the procedure described in Zhu et al. (2019). The results indicate that the flux of No.2338 shows a variability up to an order of magnitude ($10^{-6} - 10^{-5}$ photon cm$^{-2}$ s$^{-1}$), which are comparable to non-mCVs, especially dwarf novae in the solar vicinity (e.g., Wada et al. 2017). It is noteworthy that the spectral shapes appear slightly different for the spectra extracted in the high-flux and low-flux states; however, no significant deviation of the fitted $I_{\text{7.0}}/I_{67}$ can be measured due to relatively large statistical uncertainties. On the other hand, the flux of No.2942 remains constant ($\sim 7 \times 10^{-9}$ photon cm$^{-2}$ s$^{-1}$) over the last 19 yr, just like IPs in the solar vicinity. Given the high (low) variabilities and the low (high) $I_{\text{7.0}}/I_{67}$ value, No.2338 (No.2942) is likely a non-mCVs (an IP). The WD masses can be derived to be $0.36^{+0.22}_{-0.11} M_\odot$ ($0.77^{+0.25}_{-0.30} M_\odot$) for No.2338 if it is an IP (non-mCV); and $>0.63 M_\odot$ ($>1.3 M_\odot$) for No.2942 if it is an IP (non-mCV).

The implications of these values are addressed below.

4. Discussion

4.1. The Nature and Formation Channel of NSC CVs

The $I_{\text{7.0}}/I_{67}$ and the derived $T_{\text{max}}$ and $M_{\text{WD}}$ values provide important clues on the nature of NSC CVs, as discussed below. Given the 2–10 keV luminosity range, H sources are comparable to IPs in solar vicinity. Furthermore, the $I_{\text{7.0}}/I_{67}$ value

\footnote{The upper limit of WD mass of No.2942 is not constrained because the upper limit of $I_{\text{7.0}}/I_{67}$ is beyond the range of the $I_{\text{7.0}}/I_{67}$-$M_{\text{WD}}$ relation, see Figure 3 for details.}
(0.60 ± 0.05) is a little bit lower than that of IPs in the solar vicinity (0.71 ± 0.04, see Xu et al. 2016). The most natural nature of H sources is thus a mixture of IPs and non-mCVs, as is suggested by the above analysis on No.2338 and No.2942.

The situation for L sources is a little bit different. Their luminosities are consistent with non-mCVs in the solar vicinity (e.g., Revnivtsev et al. 2009; Byckling et al. 2010; Reis et al. 2013; Xu et al. 2016; Yu et al. 2018), but their mean $I_{7.0}/I_{6.7}$...
(0.92 ± 0.22) is significantly higher than those of the solar vicinity non-mCVs ($I_{7.0}/I_{6.7} \sim 0.2$, see Xu et al. 2016). The inferred $M_{\text{WD}}$ of the L sources, in particular, is to be contrasted with the average $M_{\text{WD}} \approx 0.8 M_\odot$ of the Galactic bulge CVs with similar X-ray luminosities (which were suggested to be mostly non-mCVs with averaged $I_{7.0}/I_{6.7} \sim 0.3$, see Yu et al. 2018). Now there are two possibilities, either L sources are non-mCVs with mean $M_{\text{WD}} > 1.0 M_\odot$, or they are low luminosity IPs. The formation of these CVs could be related to the dynamical encounters in the NSC, which are briefly discussed as follows.

Theoretically, the most important dynamical effects includes the gravitational influence of the SMBH, the mass segregation and close encounters between stars. The mass segregation tends to bring massive stars and binaries to the vicinity of the SMBH; the close stellar encounters can selectively bring massive stars into binaries and alter the orbits of binaries (e.g., Heggie 1975; Hills 1975; Hut 1993). As a result, the WDs of the descendent CVs are supposed to be significantly higher from their field counterparts, i.e., binaries subject only to secular stellar evolution. This scenario is also supported by the high EW of the NSC CVs, which indicates that the donor star must be relatively metal-rich ($Z > 0.6$), which is at odds with the typical metal-poor stellar populations in globular clusters, if the CVs were originally formed in globular clusters and sequently fell into the NSC (e.g., Tremaine et al. 1975; Antonini et al. 2012). This strongly suggests that the CVs presently detected in the NSC have been reprocessed (their companions have been exchanged) after their infall, which is supported by numerical simulations (Panamarev et al. 2019). On the other hand, this scenario may also favor the formation of IPs. The dynamical exchange in globular clusters and in the NSC could shrink the orbital separation, and enhance the population of close binaries. Such an effect would naturally lead to the formation of tighter

Figure 4. Cumulative Chandra ACIS-S spectra of two brightest sources in the GCXE region. Top panel: No.2338. Bottom panel: No.2942. The spectra are fitted by an absorbed bremsstrahlung plus a three-Gaussian model to characterize the three Fe emission lines. The data error bars are of 1σ.
post-common envelope binaries, which were suggested to favor the formation of mWDs (Briggs et al. 2018).

4.2. Contribution of Resolved CVs to the 20–40 keV CHXE

The unresolved 20–40 keV CHXE detected by NuSTAR was suggested to predominantly arise from a large number of IPs (Perez et al. 2015; Hailey et al. 2016). The contribution of Chandra-resolved CVs to the CHXE can be estimated by extrapolating the Chandra spectra to 40 keV, assuming a cooling flow model with $T_{\text{max}} = 23^{+8}_{-8} \text{ keV}$, which is obtained from the $I_{\gamma0}/I_{\gamma7}-T_{\text{max}}$ relation for $I_{\gamma0}/I_{\gamma7} \approx 0.65 \pm 0.20$ (Table 1). The thus derived 20–40 keV flux is $(1.7 \pm 0.4) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, which is $(24 \pm 6)\%$ of the total flux measured by NuSTAR ($\sim 7 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, see Hailey et al. 2016). A more delicate estimate comes from separately extrapolating the spectra of the GCXE-H and GCXE-L sources (the normalization of the spectra are rescaled according to the stellar mass enclosed in the GCXE and the CHXE regions), for them having different $I_{\gamma0}/I_{\gamma7}$ (hence different $T_{\text{max}}$). This results in a 20–40 keV flux of $(2.4 \pm 0.5) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, with $\sim 60\%$ from H sources and $\sim 40\%$ from L sources. The two estimates are consistent with each other, and only account for $\lesssim 42\%$ of the NuSTAR flux. This deficit might be explained if there is a large population of less luminous CVs, and/or millisecond pulsars, which were proposed to be abundant in the Galactic center region (e.g., Eckner et al. 2018).

5. Summary

We have investigated the combined X-ray spectra of the CVs located in the Galactic center region based on archival Chandra ACIS-S observations to trace their mean WD masses. We focus on the NSC region, more specifically, the half-circular region with a projected galacto-centric radius $R = 250''$ and Galactic latitude $b > 0$, defined as the GCXE region. We divide the point sources detected therein into GCXE-H (with $L_{2-10 \text{ keV}} > 6 \times 10^{31} \text{ erg s}^{-1}$) and GCXE-L (with $L_{2-10 \text{ keV}} < 6 \times 10^{31} \text{ erg s}^{-1}$) subgroups according to their X-ray luminosities. We also examine the Chandra sources falling within the central hard X-ray emission southwest (CHXE-SW) region as defined in Perez et al. (2015). Our main results and conclusions are as follows.

(a) The CVs with $L_{2-10 \text{ keV}} > 6 \times 10^{31} \text{ erg s}^{-1}$ ($L_{2-10 \text{ keV}} \sim 1-6 \times 10^{31} \text{ erg s}^{-1}$) in the NSC have a mean $T_{\text{max}}$ of $21^{+3}_{-3} (38^{+11}_{-5})$ keV, which corresponds to a mean WD mass of $0.57^{+0.02}_{-0.02} M_{\odot} (0.83^{+0.11}_{-0.11} M_{\odot})$ if the dominant CV population is made up of IPs, or $1.04^{+0.04}_{-0.03} M_{\odot} (1.25^{+0.07}_{-0.05} M_{\odot})$, if it consists of non-mCVs, respectively.

(b) The Chandra detected point sources can contribute $\lesssim 42\%$ of the 20–40 keV CHXE.

(c) The massive WDs in the CVs likely result from dynamical exchanges in the NSC.

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Facilities: CXO (ACIS), NuSTAR.

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