PERIODIC Chandra X-RAY SOURCES IN THE LIMITING WINDOW

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ABSTRACT

We have discovered 10 periodic X-ray sources and 11 candidate periodic sources from the 1 Ms Chandra ACIS observation of the Limiting Window (LW), a low extinction region (A_V ~ 3.9) at 1.4° south of the Galactic Center. The LW provides a rare opportunity of studying the Galactic Bulge sources without obscuration from molecular clouds. Of 1397 discrete X-ray sources discovered from the deep exposure images, we have searched for periodic X-ray modulation in the 843 sources with net counts greater than 50 in the 0.3–8 keV band, using three algorithms over four separate intervals of the full exposure. The period range (4.2 min to 4.4 hours) and the luminosity range (10^{30–33} erg s^{-1}) of the 21 periodic sources and candidates, combined with the lack of bright optical counterparts and thus high X-ray-to-optical flux ratios, suggest that they are likely accreting binaries, in particular, magnetic cataclysmic variables (MCVs). Of the 21 sources, 18 exhibit a relatively hard X-ray spectrum (\Gamma < 2 for a power law model) and 14 show a larger extinction in the spectrum than the field average expected from the interstellar medium in the region. The latter implies some intrinsic absorption in the system, which is also a typical sign of MCVs. Using the early 100 ks Chandra exposure and the HST observation that covers seven of these sources, van den Berg et al. (2009) have reported four sources as candidate CVs or accreting binaries, based on their blue optical colors, excess Hα fluxes, and high X-ray-to-optical flux ratios. Our observations of the LW using the IMACS camera on the Magellan 6.5 m telescope in the B, V, R, and I bands show one or two candidate counterparts within the error circle of ten sources, and all but one show relatively high X-ray-to-optical flux ratios. The discovery of the periodic X-ray sources in the LW further supports the current view that MCVs constitute the majority of low luminosity hard X-ray sources (10^{30–34} erg s^{-1}) found in the Bulge. The period distribution of these sources resembles those of polars, whereas the relatively hard spectra suggest that they could be intermediate polars (IPs). These puzzling properties, which are also shared by some of the periodic X-ray sources found in the Sgr A* field (Muno et al. 2003b), can be explained by a rare sub-class of MCVs, nearly synchronous MCVs (ns-MCVs), some of which are considered as the missing link in the evolution of MCVs from IPs to polars. While the Chandra X-ray band appears relatively more sensitive in discovering ns-MCVs, according to the completeness simulation, 20 – 30% of the hard X-ray sources in the LW are periodic. Therefore, the discovery of a relatively large number of ns-MCVs in the LW implies a large population of MCVs in the Bulge.

Subject headings: Galaxy; bulge — X-ray; binaries — cataclysmic variables

1. INTRODUCTION

The high sensitivity and superb spatial resolution of Chandra enabled population study of low-luminosity X-ray sources (L_X ~ 10^{30–34} erg s^{-1}) on Galactic scales beyond the local solar neighborhood. Several ongoing campaigns, including our own Chandra Multi-wavelength Plane (ChaMPlane) survey (Grindlay et al. 2005) aim to improve the census of the Galactic low-luminosity X-ray sources. The Galactic Bulge, in particular, has been of great interest. More than 3000 discrete X-ray sources have been discovered in the 17' x 17' region around Sgr A* (Muno et al. 2003a, 2009, hereafter M03a, M09). In ChaMPlane, we study the Bulge through our dedicated surveys of low-extinction bulge regions (“Windows survey”) and a latitudinal strip around the Galactic center (“Bulge Latitude Survey”), where thousands of X-ray sources have been also discovered (Grindlay et al. 2011; Hong et al. 2009b, hereafter H09b). Multi-wavelength follow-up of these X-ray sources has been ongoing for source classification through optical/infrared imaging and spectroscopy (e.g. Koenig et al. 2008; van den Berg et al. 2006, 2009, hereafter B06, B09).

H09b and M03a have found that the X-ray sources in the Galactic Center region (GCR) show largely homogenous X-ray properties (e.g. intrinsically hard X-ray spectra, photon power law index \Gamma < 1 for a power law model). The lack of bright IR (K<15) counterparts for the GCR X-ray sources indicates that HXMBs, once considered as a major constitute for Bulge X-ray sources, cannot account for more than 10% of the population (Laycock et al. 2005, hereafter L05). Currently the leading candidates that fit the observed properties are magnetic cataclysmic variables (MCVs) (L05; M09; H09b).

Recently we started a search for periodic ChaMPlane sources (e.g. Hong et al. 2009a, hereafter H09a), in part, to circumvent difficulties in source identification, which arise from large distances, high extinction (except for the Windows fields), and source confusion due to high stellar density in the Bulge. In this work, we report the discovery of 10 periodic X-ray sources and 11 candidate periodic sources from the 1 Ms Chandra exposure of the Limiting Window (LW), a low extinction region at 1.4° south of the Galactic center (see also H09b).

The low extinction Window fields, including the LW, provide a rare opportunity of studying the GCR source population without obscuration from molecular clouds (H09a,H09b,B06,B09). Revnivtsev et al (2009, here-
after R09) showed that the Galactic Ridge X-ray Emission (GRXE), the nature of which has been puzzling for decades, is mainly made up of discrete faint sources of known nature, primarily ABs or CVs, based on the Chandra observations of the LW. The exact composition of the discrete sources in the GRXE is not resolved (see also Revnivtsev et al. 2011). We explore the X-ray and optical properties of the 21 periodic X-ray sources and candidates in the LW and their implication for evolutionary models of MCVs and their connection to thousands of X-ray sources in the GCR.

2. X-RAY OBSERVATION AND TIMING ANALYSIS

2.1. Chandra Observation and Source Search

The LW was observed for a total of 1 Ms exposure (100 ks in 2005 and 900 ks in 2008) with the Chandra ACIS-I instrument (H09b; R09). Table 1 lists the observational history of the field. The X-ray data were analyzed as part of our ongoing ChaMPlane survey (Grindlay et al. 2005) and the analysis procedures are described in detail in Hong et al. (2005, see also H09b). In summary, we stacked all of the 13 separate pointings and searched for discrete sources in the 0.3–2.5, 2.5–8.0, and 0.3–8.0 keV band images, using the wavdetect routine. The source lists in the three bands were then cross-matched to produce a list of 1397 unique discrete sources based on the positional uncertainty of each source. Carefully checked to produce a list of 1397 unique discrete sources (see Hong et al. 2005).

For the periodicity search, we selected the 843 sources with net counts greater than 50 in the 0.3–8.0 keV band. Photon arrival times of each source were bary-center corrected by the \textit{axbary} routine in the CIAO tool (ver 3.4). Then, we applied three independent search routines to find periodic modulations in four separate intervals of the X-ray data of each of the 843 sources. The three search algorithms are the Lomb-Scargle (LS) routine (Scargle 1982), Buccheri’s \(z^2\) statistics (Z2) (Buccheri et al. 1983) and the Epoch Folding (EF) method (Leahy et al. 1983). The four intervals are grouped so that the total span of each interval does not exceed a month (Table 1) in order to minimize phase confusion arising from a long span of the exposures and the uncertainty of photon arrival times for a given period range (< 10 hr) used for the search.

For the LS routine, we generated a background subtracted light curve of each source in 12.8 s bins as an input. The background counts of a source are extracted and scaled from the photons that fell in the background annulus region around the source, which excludes the source regions of neighbors (Hong et al. 2005). For Z2, we use the arrival times of all the photons in the source aperture (within 95% PSF) as an input. No background subtraction is performed for Z2. For the EF method, we generate a background subtracted folded light curve in 15 bins for a given search period and calculate the \(\chi^2\) value of the folded light curve with respect to the assumed count rate of no periodicity.

For easy comparison, we chose a single set of independent search periods, based on the total duration of each interval, and then applied the three search routines on these periods. The search periods were selected successively, starting from the total duration (\(T\)) down to \(10^{-4}T\) by a decrement of \(\Delta P = P^2/(2T s_f)\), where we introduced an oversampling factor, \(s_f\) (\(s_f=1\) means no oversampling), in order to sample the power density spectrum (or the equivalent) relatively smoothly over the entire period search range. We change \(s_f\) logarithmically from 1.0 at the shortest period (\(10^{-4}T\)) to 4.0 at the longest (\(T\)), so that a relative increase in the number of search periods due to the introduction of \(s_f\) for smooth sam-

<table>
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<tr>
<th>Obs. ID</th>
<th>Start Time (UT: y/m/d h:m)</th>
<th>R.A. (°)</th>
<th>Decl. (°)</th>
<th>Roll (°)</th>
<th>GTI (ks)</th>
<th>Exposure (ks)</th>
<th>Group (duration)</th>
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<td>273</td>
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<td>21</td>
<td>1 (3.13 d)</td>
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<td>10.7</td>
<td>11</td>
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<td>-29.58475</td>
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<td>22.4</td>
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<td>275</td>
<td>41.4</td>
<td>45</td>
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*The selected Good Time Interval (GTI) that is based on the lack of high background fluctuations (< 3\(\sigma\)). See Hong et al. (2005). The observations are grouped into four separate intervals with durations given in days, so that the total span of each interval does not exceed a month.
The clean data set excludes the pointings, if any, where the source is located near CCD edges. The complete code optimization is expected to increase the speed by another factor of 10 according to the examples given by http://txcorp.com/products/GPULib.

3 http://www.nvidia.com
4 http://www.ittvis.com/idl
5 http://gpulib.sourceforge.net
6 The complete code optimization is expected to increase the speed by another factor of 10 according to the examples given by gpulib.
tation arising from dithering motions of the telescope, we also
exclude the obvious dithering periods (707 and 1000 s) and
their harmonics for selection unless the source lies away from
the sources with prefix 'LW'.

Next, we choose candidate periodic sources if their modu-
lation significances are greater than 4σ. Here we exclude
sources falling near CCD edges even if their periodicity is not
a simple harmonic of the dithering periods unless the peri-
docity persists in a subset of the data free of near CCD edge
events. We down select prime candidates if a clean data set
that is free of near CCD edge events, node mix or neighbor
contamination shows a periodicity with \( P_{\text{FAP}} \) less than 1% and
modulation significance greater than 4σ.

The above selection criteria are more lenient on node mix
than CCD edge events. Since we exclude the obvious dither-
ing periods, even if sources fall near CCD edges or contain
node mix, their periodicity can be valid (only one such source
in Table 3 - LW8). But sources falling near CCD edges may
suffer more complications, which may not be easily identifi-
able, so that we do not consider their periodicity valid unless a
clean data set exhibits the same periodicity. For instance, the
background annulus aperture of a source falling near a CCD
edge can include a region beyond the CCD active area, which
may influence the results of the LS and EF methods; the Z2
routine does not use events in the background region.

As shown in Table 2, the LS routine seems the most sen-
sitive (or the most prone to a false detection) among the three
routines because it has found all of the periodic sources re-
ported by the other two methods and more. In order to se-
lect valid periodicities without being subjected to a particular
reference, in addition to the X-ray source name (starting with
the prefix 'LWP'), we assign an abbreviated version of the name start-
ing with prefix 'LW'.

### Table 3: Periodic Sources in the LW

<table>
<thead>
<tr>
<th>Source ID</th>
<th>Name in CXOPS</th>
<th>Counts</th>
<th>Period (s)</th>
<th>( P_{\text{FAP}} ) (10^{-6})</th>
<th>( \Delta M )</th>
<th>Mod. Signi. ( P_{\text{det}} ) (%)</th>
<th>Offset (s)</th>
<th>GTI (ks)</th>
<th>Search Results</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWP 1 J175151.2-293310</td>
<td>1775(45)</td>
<td>10322(22)</td>
<td>23.7</td>
<td>0.64(6)</td>
<td>11.1</td>
<td>100</td>
<td>5.6</td>
<td>662</td>
<td>1.1</td>
<td>N</td>
</tr>
<tr>
<td>LWP 2 J175123.5-293755</td>
<td>393(23)</td>
<td>5132(6)</td>
<td>16.3</td>
<td>0.95(7)</td>
<td>13.5</td>
<td>100</td>
<td>2.6</td>
<td>827</td>
<td>1.2</td>
<td>H: LW25</td>
</tr>
<tr>
<td>LWP 3 J175129.1-292924</td>
<td>361(24)</td>
<td>7448(12)</td>
<td>10.0</td>
<td>0.9(1)</td>
<td>8.6</td>
<td>100</td>
<td>6.1</td>
<td>496</td>
<td>1.2</td>
<td>N</td>
</tr>
<tr>
<td>LWP 4 J175131.6-292956</td>
<td>3217(59)</td>
<td>8538(14)</td>
<td>9.3</td>
<td>0.36(6)</td>
<td>6.1</td>
<td>100</td>
<td>5.6</td>
<td>637</td>
<td>1.3</td>
<td>B: 4</td>
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<tr>
<td>LWP 5 J175133.9-292754</td>
<td>473(30)</td>
<td>6337(8)</td>
<td>9.2</td>
<td>0.91(9)</td>
<td>9.6</td>
<td>100</td>
<td>7.7</td>
<td>827</td>
<td>1.3</td>
<td>H: LW8</td>
</tr>
<tr>
<td>LWP 6 J175118.7-293811</td>
<td>329(21)</td>
<td>4731(5)</td>
<td>7.2</td>
<td>0.8(1)</td>
<td>8.9</td>
<td>100</td>
<td>3.3</td>
<td>827</td>
<td>1.3</td>
<td>H: LW8</td>
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<td>LWP 7 J175055.5-292948</td>
<td>135(31)</td>
<td>5335(6)</td>
<td>5.9</td>
<td>1.4(3)</td>
<td>5.3</td>
<td>46</td>
<td>9.1</td>
<td>827</td>
<td>1.1</td>
<td>H: LW19, A: 0.91, N</td>
</tr>
<tr>
<td>LWP 8 J175122.7-293436</td>
<td>295(20)</td>
<td>12037(85)</td>
<td>5.7</td>
<td>1.0(1)</td>
<td>7.6</td>
<td>100</td>
<td>1.5</td>
<td>363</td>
<td>1.3</td>
<td>H, E</td>
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<tr>
<td>LWP 9 J175133.6-293313</td>
<td>457(24)</td>
<td>6598(11)</td>
<td>4.9</td>
<td>0.7(1)</td>
<td>7.4</td>
<td>100</td>
<td>2.6</td>
<td>637</td>
<td>1.3</td>
<td>H: LW19, A: 0.91, N</td>
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<tr>
<td>LWP 10J175119.4-293659</td>
<td>415(23)</td>
<td>2631(2)</td>
<td>4.3</td>
<td>0.8(1)</td>
<td>8.1</td>
<td>100</td>
<td>2.4</td>
<td>827</td>
<td>1.3</td>
<td>H</td>
</tr>
</tbody>
</table>

(1) An abbreviated X-ray source ID. (2) The Chandra source name. (3) The net counts in the 0.3–8 keV band. (4) The modulation period based on the LS routine. (5) A simulation driven estimate of the False Alarm Probability (FAP). The simulations cover the range of \( n \) up to \( 5 \). An \( n \) value greater than 4.0 is based on an extrapolation of the simulation results for \( 1 < n < 4 \) (\( n \approx 4.6 - 0.46X \), where \( X \) is the power density). (6) A modulation amplitude based on Eq. 1. (7) A modulation significance, \( \Delta M / \sigma_{\Delta M} \). (8) A detection probability of periodicity based on 100 simulation runs for each source. (9) The offset from the aimpoint of Obs. ID 5934 (R.A.: 17h 51m 28.50s, DEC.: -29° 13′ 46″). (10) The GTI of the clean data set free of any near CCD edge events or node mix in the last 17.7 d interval. The maximum GTI in the interval is 827 ks. (11) The period search results in the order of LS, Z2 and EF. ‘1’ means a prime candidate, ‘2’ a candidate, and ‘0’ not a candidate. e.g. 1.20 means the source is a prime candidate periodic source according to LS and a candidate according to Z2, but not a candidate according to EF. (12) N: the source falls on a readout node boundary in some pointings, E: the source falls near a CCD edge in some pointings; H: in the Advanced Camera for Surveys (ACS) FoV of the HST observation, followed by the source ID of B09 if reported. A: the 95% PSF overlaps with neighbors. The number indicates the fractional radius of the non-overlapping region within the 95% PSF. See Hong et al. (2005). B: the number of Bayesian Blocks when multiple blocks are identified. It indicates long term variabilities.
Fig. 1.— Power density spectra, folded light curves, energy spectra and compressed light curves of the confirmed periodic X-ray sources (LWP 1–5) in the LW. The power density spectra are based on the LS method, and the 90% and 99% confidence levels are shown in (red) horizontal lines. The solid lines in the folded light curves are from the last 802 ks data set and the dotted lines from all of the data. The (red) horizontal lines show the average rates. In the energy spectra, the (red) lines show the results of simple power law model fits. In the case of LWP 1, a model fit using a power law plus an iron line is shown in blue. In the compressed light curves, the (red) horizontal lines represent the average rate, the (green) steps show the effective area of each pointing, and the (yellow) vertical lines indicate the removed exposure gaps (> 20 ks). In the case of LWP 4, the Bayesian Blocks are shown in blue lines.

Compressed light curves without long exposure gaps of the 21 periodic sources and candidates. The power density spectra are based on the LS method, which is applied to the last 802 ks exposure acquired in the 17.7 d interval. The power density spectrum of LWP 8 is from the last 352 ks exposure in 8.1 d when the source was observed well inside the CCD. Two folded light curves are shown for each source: one from the same data set used to generate the power density spectrum (solid) and the other from all of the available data (dotted), which amount to about 963 ks. The X-ray spectrum of each source is generated using all of the available data, and each spectral bin contains more than 25 counts (before background subtraction). The red solid lines show the results using a simple power law model fit, and the blue lines show other suitable model fits for three sources (a power law plus an iron line for LWP 1 and 12, and an APEC model for LWP 21). The spectrum model fit is shown only for the sources with net counts greater than 150. The compressed light curves are generated by removing the long exposure gaps (> 20 ks), which are marked by the yellow vertical lines. The red horizontal lines show the average count rate and the green lines show the effective area, which varies from pointing to pointing. The blue solid lines show the count rates calculated by the BB search when two or more independent blocks are found from the search (LWP 4 and 16).

Table 4 summarizes the X-ray spectral properties, based on spectral model fits for bright sources with net counts greater than 150 or quantile analysis for the rest (Hong et al. 2004). We test all the sources using a simple power law model, and for the following five sources, we also use another model in addition. Two sources (LWP 1 and 12) are found to be better fit by a power law model with an iron line, which is another indication of accreting MCVs. For two faint sources of the three soft sources, we estimate the plasma temperature of 3.1 and 1.8 keV using a thermal Bremsstrahlung model by quantile analysis. For the bright, soft source (LWP 21), we estimate the plasma temperature of 0.66 keV using an APEC model fit. We estimate the X-ray flux of the sources according to the derived model parameters for each model. The flux estimates in the 2–8 keV band are relatively robust regardless of the as-
sumed spectral model types for the range of the absorption observed here ($< 10^{22} \text{ cm}^{-2}$) (Hong et al. 2009b), but the flux estimates in the 0.5–2 and 0.3–8 keV bands can vary noticeably, depending on the model choice. For instance, LWP 21 shows a factor of 3 variations in the flux estimate of the 0.5–2 keV band between the two spectral models used in this analysis.

Fig. 5 shows a three color X-ray image of the LW region. The periodic sources and candidates are labeled in black, and the Advanced Camera for Surveys (ACS) fields of HST are shown in blue. The 0.3–2 keV band is represented in red, the 2–4 keV band in green, and the 4–8 keV band in blue. A section in the middle lower part of the image shows a streak of a lower extinction region, which appears redder than the rest. Two periodic sources (LWP 2 and 6) in this lower extinction region exhibit hard X-ray spectra with intrinsic absorption. The spatial distribution of the periodic sources do not show any sign of clustering.

3. OPTICAL OBSERVATION AND PROPERTIES

We observed the LW field with the HST and Magellan telescope. Of the 21 sources, seven sources are in the HST/ACS fields (B09), and four of them were reported as possible candidates for accreting binaries or CVs. For easy reference, the short names used by B09 are noted for the four sources in Table 3 (e.g. LWP 2 = LW 25).

3.1. HST/ACS Data and Analysis

We observed with HST the inner area of the ACIS field with a 2×2 mosaic of the Wide Field Camera (WFC) on the ACS on 2005 August 19. A single WFC pointing images a 3.4′×3.4′ field with ~0.05″ pixels using two CCD detectors separated by a 2.5″ gap. Exposures were taken through the F435W (B435), F625W (R625, similar to Sloan r), and F658N (Hα) filters. Each tile of the mosaic was observed with the same exposure sequence 4×492 s in F435W, 168 s + 2×167 s in F625W, and 4×496 s + 4×492 s in F658N. No dithering was applied to fill in the WFC chip gap. Photometry is performed using a stellar-photometry package, DOLPHOT, a modified version of the HSTphot package to do photometry on HST/WFPC2 images (Dolphin 2000). See B09 for the details.

3.2. Magellan/IMACS Data and Analysis

On 2007 May 8, we observed the LW field and two other Window fields (Stanek’s and Baade’s) with the Inamori Mag-
ellan Areal Camera and Spectrograph (IMACS) on the 6.5 m Magellan (Baade) telescope at Las Campanas, Chile. With seeing $\sim 0.8 - 1.2''$ FWHM, we obtained a dithered set of 5 pointings in the f/4 configuration (15.4'' field, 0.11''/pixel) to cover an 18'' $\times$ 18'' region of the LW. This provided a total exposure time of 600, 300, 180, & 180 s in Bessell-$B$, $V$, $R$, & CTIO-$I$ filters over the Chandra field respectively.

We processed the images using standard IRAF tasks, and calibrated the astrometry using the 2MASS catalog as a reference. The astrometric residuals on each CCD frame were $\sim 0.2''$. We reprojected and stacked the images using the SWARP\textsuperscript{7} utility. All frames were normalized to ADU/second units and combined using weight-maps constructed from flatfields and bad pixel masks. The initial source search and photometry were performed on the stacked images using DAOPHOT. See also H09a.

3.3. Optical Matches

Both the HST and IMACS source lists are boresighted to the Chandra sources as described in Zhao et al. (2005): the boresight correction is less than 0.1'' in both R. A. and Declination. Table 5 summarizes the combined optical and X-ray properties of the candidate optical counterparts of the Chandra sources. For the seven sources in the HST/ACS fields, we use the HST results, and for the rest, we use the Magellan/IMACS results. Out of the remaining 14 sources, five sources have one or two candidate counterparts detected in the Magellan/IMACS images, but considering high stellar density in the region, there is no guarantee of these Magellan/IMACS sources being the true counterparts (e.g. LWP 9 has six can-

\textsuperscript{7}http://www.astromatic.net/software/swarp
The X-ray-to-optical flux ratios, $\log(F_X/F_\text{opt})$, in Table 5 are calculated for the 0.3–8 keV band vs. the $R$ magnitude. Both the observed and unabsorbed flux ratios are given. For unabsorbed flux ratios, the $R$ magnitude is dereddened based on the $A_{F625W}$ map given by Revnivtsev et al. (2010). For sources with multiple candidate counterparts, a range of the $R$ magnitude and the flux ratio is given, covering all the candidate counterparts. In the case of LWP 6 (= LW 8) and LWP 2 (= LW 25), shown is the $R$ magnitude of the most likely candidate with an unusually blue color (B09). In the case of LWP 11, only one of the candidate counterparts has a measurable $R$ magnitude. For sources with no detectable candidate counterparts, a lower limit for the $R$ magnitude is given, based on the minimum value of optical neighbors within a $30''$ radius of the X-ray source position. For three sources (LWP 14, 15 and 19) with relatively bright optical neighbors, the given lower limit of the $R$ magnitudes and the flux ratios are likely underestimated since contamination from neighbors usually degrades detection sensitivity.

The logarithmic flux ratios or their limits of these periodic sources are relatively high: $>-1$ for 13 sources and $>-2.4$ for 19 sources. The intrinsic X-ray-to-optical flux ratios of accreting binaries or AGN are usually significantly higher than those of coronal sources (see §4.1.2 in B09 and the references therein). CVs have the intrinsic flux ratio between $-2.4$ and $-0.5$ in the above energy bands, although a few outliers of active binaries or dMe stars have the flux ratios as high as $-1$ or $-0.5$. Therefore, the flux ratio results in Table 5 are consistent with those of CVs.

Note that most of the flux ratio values in Table 5 are in fact likely the lower limits except for a few cases with an outstanding blue counterpart, considering high stellar density in the region. Some (LWP 5, 7, 11 & 20) have additional uncertainties in their estimates due to the variation in the interstellar absorption across the region: for these sources, the $A_{F625W}$ values were sampled about 3 or $4''$ away from the sources. For six or seven sources (depending on the spectral models), the absorption in the X-ray spectra is estimated less than what is expected in the field, based on $A_{F625W}$. LWP 21 has the lowest flux ratio value with the softest X-ray spectrum.

4. SOURCE PROPERTIES

In this section, we discuss some of the unique properties or analysis caveats of each source.
The luminosity range in the 0.3–8 keV band for source distance at 1–8 kpc. The assumed spectral model is a power law model.

<table>
<thead>
<tr>
<th>Source ID</th>
<th>$E_{\text{peak}}$ (keV)</th>
<th>$N_{\text{H122}}$</th>
<th>$\Gamma$</th>
<th>$kT$ or EW (keV)</th>
<th>$\chi^2/\text{DoF}$</th>
<th>Unabsorbed Flux (0.3–8 keV)</th>
<th>Luminosity (erg cm$^{-2}$ s$^{-1}$)</th>
<th>Model</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confirmed Periodic Sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LWP 1</td>
<td>3.86(6)</td>
<td>1.4(1)</td>
<td>0.42(2)</td>
<td>41.8/67</td>
<td>6.2(5)</td>
<td>56.1(1)</td>
<td>63.2</td>
<td>30.9–32.7</td>
<td></td>
</tr>
<tr>
<td>LWP 2</td>
<td>2.9(1)</td>
<td>2.1(2)</td>
<td>1.87(6)</td>
<td>5.0/14</td>
<td>8(1)</td>
<td>8.8(6)</td>
<td>20.1</td>
<td>30.4–32.2</td>
<td></td>
</tr>
<tr>
<td>LWP 3</td>
<td>3.72(2)</td>
<td>2.2(3)</td>
<td>1.18(6)</td>
<td>9.5/16</td>
<td>2.9(8)</td>
<td>10.5(7)</td>
<td>14(1)</td>
<td>30.2–32.0</td>
<td></td>
</tr>
<tr>
<td>LWP 4</td>
<td>3.36(4)</td>
<td>1.4(7)</td>
<td>1.12(2)</td>
<td>70.4/109</td>
<td>23(1)</td>
<td>79(2)</td>
<td>107(2)</td>
<td>31.1–32.9</td>
<td></td>
</tr>
<tr>
<td>LWP 5</td>
<td>3.4(2)</td>
<td>1.0(2)</td>
<td>0.92(6)</td>
<td>16.6/27</td>
<td>3.1(5)</td>
<td>12.6(9)</td>
<td>16(1)</td>
<td>30.3–32.1</td>
<td></td>
</tr>
<tr>
<td>LWP 6</td>
<td>3.2(1)</td>
<td>1.2(2)</td>
<td>1.20(6)</td>
<td>7.2/12</td>
<td>2.2(3)</td>
<td>6.9(5)</td>
<td>9.5(6)</td>
<td>30.1–31.9</td>
<td></td>
</tr>
<tr>
<td>LWP 7</td>
<td>4.1(4)</td>
<td>0.67(1)</td>
<td>−0.31(0)</td>
<td>0.3(2)</td>
<td>7(1)</td>
<td>7(2)</td>
<td>29.9–31.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LWP 8</td>
<td>3.8(1)</td>
<td>0.2(1)</td>
<td>0.05(6)</td>
<td>8.09</td>
<td>0.42(8)</td>
<td>7.8(6)</td>
<td>8.0(5)</td>
<td>30.0–31.8</td>
<td></td>
</tr>
<tr>
<td>LWP 9</td>
<td>2.9(1)</td>
<td>0.6(1)</td>
<td>0.98(6)</td>
<td>17.4/15</td>
<td>2.2(2)</td>
<td>8.0(5)</td>
<td>10.7(6)</td>
<td>30.1–31.9</td>
<td></td>
</tr>
<tr>
<td>LWP 10</td>
<td>3.58(9)</td>
<td>1.3(2)</td>
<td>0.93(5)</td>
<td>6.0/14</td>
<td>2.3(3)</td>
<td>9.6(6)</td>
<td>12.3(7)</td>
<td>30.2–32.0</td>
<td></td>
</tr>
<tr>
<td>Candiate Periodic Sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LWP 11</td>
<td>3.0(2)</td>
<td>1.8(3)</td>
<td>1.78(7)</td>
<td>14.3/26</td>
<td>7(1)</td>
<td>8.3(7)</td>
<td>17(1)</td>
<td>30.3–32.1</td>
<td></td>
</tr>
<tr>
<td>LWP 12</td>
<td>3.46(8)</td>
<td>1.8(2)</td>
<td>1.25(4)</td>
<td>20.7/31</td>
<td>6.8(8)</td>
<td>19.9(9)</td>
<td>28(1)</td>
<td>30.5–32.3</td>
<td></td>
</tr>
<tr>
<td>LWP 13</td>
<td>4.0(3)</td>
<td>0.96(1)</td>
<td>0.11(2)</td>
<td>3.1(3,8)</td>
<td>0.3(3)</td>
<td>3.6(7)</td>
<td>3.9(6)</td>
<td>30.6–32.4</td>
<td></td>
</tr>
<tr>
<td>LWP 14</td>
<td>2.9(1)</td>
<td>1.6(2)</td>
<td>1.63(5)</td>
<td>17.2/75</td>
<td>7.8(12)</td>
<td>12.5(7)</td>
<td>22(1)</td>
<td>30.4–32.2</td>
<td></td>
</tr>
<tr>
<td>LWP 15</td>
<td>1.9(3)</td>
<td>1.0(2)</td>
<td>2.5(3)</td>
<td>3.1(3,8)</td>
<td>0.3(3)</td>
<td>3.6(7)</td>
<td>3.9(6)</td>
<td>30.1–31.9</td>
<td></td>
</tr>
<tr>
<td>LWP 16</td>
<td>3.6(2)</td>
<td>0.9(4)</td>
<td>0.71(9)</td>
<td>2.5/5</td>
<td>0.7(2)</td>
<td>4.1(5)</td>
<td>5.0(5)</td>
<td>29.8–31.6</td>
<td></td>
</tr>
<tr>
<td>LWP 17</td>
<td>3.7(4)</td>
<td>0.71(10)</td>
<td>0.11(7)</td>
<td>0.2(1)</td>
<td>0.2(1)</td>
<td>4.0(6)</td>
<td>4.2(6)</td>
<td>29.7–31.5</td>
<td></td>
</tr>
<tr>
<td>LWP 18</td>
<td>1.3(1)</td>
<td>0.57(2)</td>
<td>2.7(5)</td>
<td>3.1(3,8)</td>
<td>0.3(3)</td>
<td>3.6(7)</td>
<td>3.9(6)</td>
<td>29.6–31.4</td>
<td></td>
</tr>
<tr>
<td>LWP 19</td>
<td>2.83(7)</td>
<td>1.09(8)</td>
<td>1.43(4)</td>
<td>25.0/34</td>
<td>8.6(6)</td>
<td>18.8(0)</td>
<td>29.1</td>
<td>30.5–32.3</td>
<td></td>
</tr>
<tr>
<td>LWP 20</td>
<td>2.7(2)</td>
<td>0.9(2)</td>
<td>0.83(9)</td>
<td>7.3/16</td>
<td>1.9(3)</td>
<td>10.2(9)</td>
<td>12.3(9)</td>
<td>30.2–32.0</td>
<td></td>
</tr>
<tr>
<td>LWP 21</td>
<td>1.12(0)</td>
<td>0.06(2)</td>
<td>3.8(5)</td>
<td>2.9(6)</td>
<td>1.7(2)</td>
<td>0.1(1)</td>
<td>4.6(5)</td>
<td>29.7–31.5</td>
<td></td>
</tr>
</tbody>
</table>

(1) An abbreviated X-ray source ID. (2) $R$ magnitude, based on the HST observation if available, otherwise, based on the Magellan Images. For sources with multiple counterparts, the range of those counterparts is given. For sources with no valid counterparts, a lower limit is given, based on the minimum magnitude of neighboring optical sources within a 30" radius from the X-ray source position. * uses the $J$ magnitude instead of $R$. † due to bright neighbors, the lower limit may be underestimated: the same for Log(Fx/Fk). (3) $B$ (F435W) – $R$ (F625W) from the HST observation or $R$ – $I$ from the Magellan IMACS images. (4) 10$^{−3}$ erg cm$^{-2}$ s$^{-1}$. Based on spectral fits or quantile analysis. See column (7) in Table 4. (5) Log(Fx/Fk) + Log(Fz/Fk) + $R$ + 2.5/5.76. For unabsorbed flux ratios, the $R$ magnitudes are dereddened by $A_{R395}$ and the unabsorbed X-ray fluxes from the spectral fits or the quantile analysis are used. (7) $A_{0625}$ from Revnivtsev et al (2010) and Degree of Freedom (DoF) for spectral model fits.
4.1. LWP 1: CXOPS J175151.2-293310

This source shows a significant periodicity at both the primary period (10322 s) and its harmonics (5161 s) according to the LS method. The EF method finds the primary period and its longer harmonics (e.g. 20645 s) significant, and the folded light curve shows a similar modulation for both. The X-ray spectrum shows iron lines consistent with 6.4 and 6.7 keV. The hard spectrum and iron emission lines suggest an IP is likely the source type but the observed period implies a polar might be statistically the right type (e.g. only two IPs with > 10^3 s spin period in Fig. 8a, see §6.1 for the details).

4.2. LWP 2: CXOPS J175123.5-293755

This source was reported as a possible accreting binary (LW 25) in B09. Two optical sources in the HST/ACS images are found within the error circle of the X-ray source position, and neither of them stands out with any unusual colors.

4.3. LWP 3: CXOPS J175129.1-292924 & LWP 14: CXOPS J175152.4-293244

These sources exhibit a mild anti-correlation between the count rate and the absorption in the X-ray spectrum according to the phase-resolved quantile diagram (Fig. 6). This anti-correlation is consistent with a picture that the observed X-ray modulation is caused by the variation of intrinsic absorption in the system, similar to the IP discovered in BW (Hong et al. 2009a). Alternatively if the X-ray modulation originates from an eclipse or an obscuration of the hot spot or the emission region due to the spin or orbital motion, then the absorption variation is not expected to be strongly correlated with the rate change.

4.4. LWP 6: CXOPS J175118.7-293811

This source was reported as a CV candidate (LWP 6 = LW 8) by B09, based on the high X-ray-to-optical flux ratio and Hα excess (see Fig. 4 in B09). From the LS analysis, the X-ray emission shows a significant modulation at both of the primary period (4731 s) and the one-third (1576 s). One can interpret this as the orbital and spin periods (or their beating period), but the ratio of the two periods being exactly one-third suggests that they are likely related, perhaps a harmonic of each other. In addition, according to the EF analysis, the primary period and the second multiple (9461 s) appear significant, whereas the Z2 method finds only the primary period significant. The folded light curve at the primary period shows a primary peak and a smaller secondary peak about 0.33 phase apart (Fig. 7a), which is the origin of the observed modulation at the one-third of the primary period. The folded light curve at the longer period (9461 s) shows two peaks about 0.5 phase apart (Fig. 7b).

The phase-resolved quantile analysis at the longer period (9461s) shows a clear change in the absorption between the first and second halves of phase, as shown in Fig. 7b, whereas the other two shorter periods do not show such a state change (the case for the 4731 s period shown in Fig. 7a for comparison). A state change of the absorption between two peaks in the folded light curve would suggest that two magnetic poles of the system are visible in turn, and the X-ray emission from one of them undergoes absorption from more material (likely an accretion curtain, trailing to a pole and extended from about half of the accretion disk or ring) before reaching us. Fig. 5 in Evans & Hellier (2007) illustrates a possible viewing geometry for such a system: unlike the cases described in Evans & Hellier (2007), the soft blackbody component (\(< 1\) keV) of LWP 6 is likely always invisible due to the interstellar absorption, but the geometry allowing for the phase-dependent variation of intrinsic absorption due to the accretion stream or curtain does apply to LWP 6. This result suggests that the longer period (9461 s) is a real period (likely the spin period), and the observed primary period (4731 s) and its one-third (1576 s) are in fact the harmonics.

4.5. LWP 8: CXOPS J175122.7-293436

During three pointings out of 13 total, this source fell near an edge of a CCD (see the effective area in Fig. 2), which would discredit the observed periodicity, but the clean data set (the last 352 ks) free of near CCD edge events also exhibits a significant periodicity at 12037 s according to the LS and Z2 methods, so that the source is selected as a confirmed periodic source.

4.6. LWP 7, 9, 13, 16, and 20

The aperture source region (95% PSF) of these sources overlaps with that of a neighbor. In the case of LWP 7 and 9, the clean data set relatively free of the contamination from the neighbor (see Hong et al. (2005) for aperture choice) exhibits the same periodicity. LWP 9 (= LW 19) was reported as a potential accreting binary by B09. For the other three sources, the clean data set does not show the same periodicity, which is in part due to a low statistics (e.g. total 68 net counts in 0.3–8 keV for LWP 13). In the case of LWP 13 and 16, the aperture overlap with the neighbor is relatively minor. LWP 20 is the only source with a substantial overlap: the non-overlapping fractional radius of the source aperture is 0.55, as listed in Table 3 (1.0 means no overlap), but due to a large offset (8.3`) of the source from the aimpoint, it is not clear its neighbor is indeed a separate source. Further observation is required to resolve the potential contamination in the analysis.

4.7. LWP 11: CXOPS J175147.4-294215 & LWP 17: CXOPS J175138.3-293330

Both of these sources show a significant periodicity between 20 and 40 sec in the LS periodogram in addition to the primary periods. If these short periods are real, it is likely that they are the spin periods and the primary periods (4886 s and 5158 s) are the orbital periods. However, these short periods are not too far from the CCD readout time cycle (~ 3.2 s) and the folded light curve at these periods do not show a convincing modulation, so they are not considered as a real periodicity. In addition, for a MCV with orbital period below the period gap (< 2 – 3 hr), such a short spin period does not fit popular evolutionary models. According to Norton, Wynn & Somerscales (2004), the orbital periods of IPs tend to decrease and the spin periods increase, as they evolve toward a more synchronized system through magnetic lock. Consequently, systems below the period gap are expected to be more synchronized: a larger fraction of MCVs below the period gap show a high spin-to-orbital period ratio (P_s/P_o) than those above the period gap (see also Fig. 8 and §5.1). Therefore, if the short periodicities found in these systems turn out to be real spin periods, they may be on a different evolutionary path.

4.8. LWP 18: CXOPS J175118.1-293332

This source (= LW 2) is reported as a candidate CV or dMe star in B09. The observed period (16004 s) is a multiple of the
**Figure 5.** A three color image of the LW region ($\sim 20' \times 20'$). The 0.3–2 keV band is in red, the 2–4 keV band in green, and the 4–8 keV band in blue. The periodic sources and candidates are labeled in black. The *HST*/ACS fields are shown in the blue boxes.

**Chandra*/ACIS dithering period (1000 s), but since the source was not near any CCD edges or node boundaries, it remains as a candidate periodic source. If the observed periodicity is real, it implies the source is likely a CV since dMe stars tend to exhibit quasi-periodic variability such as flares.

### 5. Discussion

In this section, we explore the most probable source types for the periodic sources found in the LW and their implications. We also investigate the hidden population of periodic sources in the Bulge X-ray sources in the GCR through completeness simulations for periodicity detection.

#### 5.1. Common or unusual MCVs: Near Synchronous MCVs?

For clarity, we limit the discussion to the first 10 sources with more securely identified periodicity in Table 3. The statistical significance of the conclusion of this section remains high even if we include all the 21 sources in the table. The observed source properties such as the X-ray luminosity range ($\sim 10^{30-33}$ erg s$^{-1}$ for distance of 1 – 8 kpc), the relatively hard X-ray spectra ($\Gamma < 2$), the period range (40 min – 3.3 hr), and the relatively high X-ray-to-optical flux ratios, all indicate that these sources are typical MCVs. But the collection of these properties does not appear to fit well with most common types of MCVs as explained below.

MCVs can be largely divided into two groups, IPs and polars, depending on the relative strength of the magnetic fields. Traditionally, polars are synchronized or nearly synchronous ($P_s/P_o \sim 0.98 – 1.02$), whereas IPs are not ($P_s/P_o \lesssim 0.1$). Fig. 8 shows the spin vs. orbital period distribution of the MCVs in the Ritter & Kolb (RK) catalog (Ritter & Kolb 2003). In Fig. 8a, the observed periods of the periodic X-ray sources found in the LW and Sgr A* fields are shown as orbital periods along $P_s/P_o = 2$ or 4 for easy comparison.

In the case of the confirmed periodic sources in the LW, the observed period distribution (solid red in Fig. 8b) resembles those of polars (green) better than either the spin (black) or orbital (blue) periods of IPs. Some IPs do have spin or orbital periods at around an hour to three hours, but the majority of the spin (or orbital) periods are shorter (or longer), whereas the majority of the periods of polars are in the same range as those of the periodic sources in the LW.

In order to find out if the above result is due to a period-dependent selection bias in the periodicity search routines, we have conducted a set of simulations using synthetic light curves with various net counts (100 to 500), modulation amplitudes (40% to 100%) and periods ($\sim 160$ to 30000 sec). The simulation results show there is no significant selection bias in the trial period range, implying that the resemblance to the polar period distribution is not due to any selection ef-
Fig. 6.— Phase-resolved quantile diagrams of (a) LWP 3 and (b) LWP 14 using the last 801 ks exposure. The top panels show the folded light curves using sliding windows of variable bin size (to fix the source counts in each bin: example data points with bin sizes are shown in phase 0 – 1) and the error bars are color-coded by phase for easy comparison. The middle panels show the phase-resolved quantile diagrams. The bottom panels show the rate vs. the quartile ratios (y-axis of the quantile diagrams in the middle panels), where the latter is mostly proportional to \( \log(N_{H22}) \) for these sources. The same example data points in the top panels are shown with error bars in the middle and bottom panels.

in the search algorithms\(^8\), or if these sources are IPs, they indeed belong to a statistically different population from the typical IPs.

The lack of the observable secondary periods from all the sources in Table 3 (with a possible, but unlikely, exception of LWP 6, see §4.4) indirectly supports the systems being polars - (nearly) synchronized systems, although non-detection does not guarantee the absence of the secondary periods.

If the X-ray emission originates from a small spot (e.g. polar cap) on the white dwarf, the modulation due to the spinning motion of the compact object is expected to exhibit a larger amplitude change than that from the orbital motion. For instance, a sample of IPs in Fig. 9, selected from the literature, also show a slightly higher average value of the modulation amplitude from the spin periods (black closed circles) than from the orbital periods (black open circles). However, note the modulation distributions of the literature-selected IPs and polars in Fig. 9 are likely selection biased: e.g. 17 polars in Fig. 9 are mostly eclipsing systems, which are likely preferentially found in periodicity searches due to the large modulation amplitude.

One can, therefore, argue that the periodic sources in the LW can be regular IPs with relatively long spin periods or eclipsing IPs with relatively short orbital periods, and they are preferentially identified due to the selection bias for high modulation sources. Such an interpretation, however, still does not explain the reason for finding many short orbital or long spin periods since there is no period dependent selection bias in the search routines. In summary, the period distribution suggests the periodic sources in the LW are mostly polars.

Unlike the period distribution, the relatively hard X-ray spectra of the periodic sources in the LW imply that these systems are likely IPs. The quantile diagrams in Fig. 10 il-

\(^8\) There is, however, a selection bias for sources with high modulation amplitudes, as expected. See §5.2.
Fig. 7.— Same phase-resolved quantile diagrams as Fig. 6, but for LWP 6 at (a) the primary period (4731 s) and (b) the second harmonic (9461 s). The bottom panels show the rate vs. the phase-resolved estimates of $N_{H_2}$ using the quantile diagrams (middle panels) with power law models. In (b), the first half of the phase (0.0–0.5) shows a higher absorption ($N_{H_2} \sim 2.5$) than the second half (0.5–1.0) ($N_{H_2} \lesssim 1.0$).

Illustrate the overall spectral hardness of the sources. Fig. 10a and b overlay a set of simple power law and APEC model grids respectively over the same data points. In Fig. 10b the confirmed periodic sources are shown in (red) filled circles, and the candidates in (blue) open circles. The eight periodic sources found in the Sgr A* field are shown in (green) crosses (Muno et al. 2003b). Three of the candidate periodic sources (LWP 15, 18, and 21) show a relatively soft spectrum, and the rest show an intrinsically hard spectrum, similarly to the periodic sources in the Sgr A* field.

It is known that IPs tend to show harder X-ray spectra, which are associated with higher accretion rate and weaker magnetic fields (Ramsay & Cropper 2004). For instance, in the case of polars, the X-ray spectra are well described by a blackbody component with $kT < 60$ eV and a two-temperature thermal plasma component with $kT_1 = 0.7–0.9$ keV and $kT_2 = 3–5$ keV (e.g. Ramsay et al. 2004b), whereas the X-ray spectra of IPs show a blackbody component with $kT > 60$ eV and a one or two-temperature thermal plasma component with $kT \gtrsim 10$ keV (e.g. Anzolin 2008). Due to the interstellar absorption in the LW field ($N_{H_2} \sim 0.7$), the blackbody component is usually undetectable, but the spectral distinction of the plasma components between polars and IPs remains detectable in the Chandra X-ray band: in a quantile diagram, polars would lie in the upper-left section of $kT \sim 4–10$ keV line, and IPs in the lower-right section (Fig. 10). Although the above description of the X-ray spectra of IPs and polars is over-simplified and without a systematic survey, it is generally accepted that IPs exhibit a harder spectrum. For instance, a recent survey of hard X-ray sources ($\gtrsim 15$ keV) conducted by Swift/BAT and INTEGRAL/IBIS shows that the composition of MCVs in the hard X-ray band are predominantly IPs (Scaringi 2010).

The period range and the relative hard spectra of the LW periodic sources also resemble those of some of the periodic sources found in the Sgr A* field (green data points in Fig. 10 and blue points in Fig. 8) (Muno et al. 2003b). Of eight periodic sources in the Sgr A* field, four are in the same period...
range as the LW periodic sources with a large modulation amplitude (>40%), and all of them show relatively hard spectra. One of them was identified as a foreground polar, based on the light curve, and it lies at the line of $\kappa T = 10$ keV and the rest lie in the $kT > 10$ keV section. In the case of the Bulge X-ray sources in the Sgr A* field, the heavy interstellar absorption ($\sim 6 \times 10^{22}$ cm$^{-2}$) complicates identification of the intrinsic X-ray spectra, but for the periodic sources in the LW ($\sim 7 \times 10^{21}$ cm$^{-2}$), there is little doubt that most of them exhibit very hard X-ray spectra.

An obvious question, then, is, what is the nature of the periodic X-ray sources found in the LW and the GCR, whose period distribution resembles polars’ but X-ray spectra resemble IPs’? A rare subclass of MCVs, nearly synchronous MCVs (ns-MCVs), perhaps meet both of the observed properties - the period distribution and the relative hard spectra of the periodic sources in the LW. One can divide ns-MCVs in two subgroups - nearly-synchronous IPs (ns-IPs) and asynchronous polars (APs). Both subgroups may exhibit similar X-ray properties, but probably represent different stages in the evolutionary path of MCVs.

First, APs, consisting originally of just four systems, which recently extended to seven according to the latest RK catalog, are traditionally considered as polars that are temporarily out of synchronization due to a recent Nova activity in which nova explosions have altered their magnetic locking, giving $P/\nu_{0} \sim 0.98–1.02$. Interestingly it is speculated that APs exhibit a harder spectrum than normal polars, but with the similar periodicities, as marked with purple diamonds in Fig. 8a. For instance, two of seven APs as opposed to two of 92 normal polars are found in the hard X-ray survey using INTEGRAL/IBIS, Swift/BAT and Suzaku/HXD (Scaringi 2010).

Second, there are increasingly more IPs found near asynchronous ($P/P_{0} > 0.3$). Starting with EX Hya, the list increases to six according to the RK catalog. Their orbital periods are predominantly around 1.5 hr except for V697 Sco with a 4.5 hr orbital period. According to the evolutionary model of Norton et al. (2008, hereafter N08), IPs start out with $P/\nu_{0} < 0.1$ and as the systems evolve through magnetic locking, the orbital periods decrease and the spin periods increase, i.e. $P/\nu_{0}$ approaches 1. Therefore, the orbital periods of ns-IPs will be clustered around or below the period gap near the end of the evolution, similarly to the periods of the periodic sources in the LW.

These ns-MCVs indeed seem to meet the observed X-ray properties of the periodic sources in the LW. In fact, the pres-
of ns-MCVs is very intriguing in terms of the evolution of MCVs, challenging the conventional view of IPs with $P_r/P_o \lesssim 0.1$ and polars $\sim 0.98 - 1.02$. For instance, Paloma or RX J0524+42 (Pineault et al. 1987), recently identified as an AP, shows $P_r/P_o \sim 0.93$, and its relatively large desynchronization ($\sim 7\%$) compared to the conventional APs ($< 2\%$) suggests that this system might represent the missing link of the evolutionary path between IPs and polars (Schwarz et al. 2007), rather than polars being out of synchronization temporarily due to recent Nova activities. As shown in Fig. 8a, the gap ($\sim 0.3 - 0.95$) in the period ratio between IPs and polars are now more or less bridged by the recent discoveries of many ns-MCVs. It is speculated that some of these ns-MCVs transit between IPs and polars (e.g. V1025 Cen, see Hellier, Wynn & Buckley 2002b).

According to N08, if the period ratio exceeds 0.6, the only stable equilibrium is at synchronization ($P_r/P_o = 1$). Schwarz et al. (2007) suggest that the probability of finding ns-MCVs is very low, considering relatively short timescale for synchronization ($< 1$ Myr) compared to the lifetime of a CV ($\sim 100$ Myr) (see also N08). Therefore, if many of the periodic sources in the LW are indeed ns-MCVs, it imposes another constraint on the evolutionary model or suggests an unusual environment of the Galactic Bulge capable of haboring many such rare systems.

It is known that the relative composition of source types in MCVs are highly biased, depending on search wavelengths. In the RK catalog, where most of the discoveries are based on optical/UV or longer wavelength bands, the relative ratio of IPs vs. polars are close to 1 (e.g. 85 IPs vs. 106 polars in Fig. 8), whereas the hard X-ray survey ($\gtrsim 15$ keV) in (Scaringi 2010) revealed 37 IPs and only 2 polars (both are APs). Therefore, if many of the periodic sources in the LW are indeed ns-MCVs, it indicates the Chandra X-ray band is well tuned for discovery of these rare ns-MCVs.

Finally we note that some of the observed X-ray properties of the periodic X-ray sources in the LW are shared by a group of quiescent Low Mass X-ray Binaries (qLMXBs). For instance, Swift J1353.5-0127, recently observed in an outburst as a black hole (BH) transient, may have a relatively short orbital period ($\sim 2$ hr, see Casares et al. 2011) and exhibit a hard X-ray spectrum (Krimm, Kennea & Holland 2011). The observed over-abundance of X-ray transients within 1 pc of Sgr A* (cf. 4 out of 7 within 20 pc, see Muno et al. 2005) implies that a large number of qLMXBs may be present as dark stellar remnants within 1 pc of Sgr A* (Schodel et al. 2007). However, CVs (and MCVs) are dominantly more abundant than these BH transients, and the periodic X-ray sources in the LW do not exhibit any strong outbursts in the 1 Ms exposure spanned over 3 years (out of 7 X-ray transients in the Sgr A* field, 3 or 4 sources seen in outbursts in each year, see Denneau & Wijnands 2009, 2010) it is reasonable to think that the large fraction of the periodic sources in the LW are in fact MCVs.

5.2. Periodic source content in the GCR X-ray source population

In this section, we estimate the number of periodic X-ray sources in the LW through completeness simulations for periodicity detection. We have generated 100 synthetic light curves for a given set of X-ray modulation parameters including modulation period and amplitude, total net count and background count. Then we run the same detection algorithm to see how often the synthetic light curves are detected as periodic. The simulation is done for the 17.7 d interval with the same GTI gaps. The initial set of simulations indicates that the detection results do not depend on the given period range (160 sec to 10 hr), so we fix the period at 5432.1 sec and varied the rest of the parameters. The simulated modulation amplitude ranges from 10 to 100% in 10% increasements. The net counts of sources are 50, 100, 200, 500, and 1000, and the background counts are 50, 100, 200, 500, and 1000. The average background count of the sources is about 200.

Using these simulation results, which cover most of the parameter space for the sources found in the LW, we interpolate the periodicity detection probability of the 843 sources in the LW with net counts greater than 50. Since we do not know a priori the distribution of modulation amplitude, we randomly assign a modulation amplitude to each source, assuming a uniform distribution from 0 to 1. We repeat the interpolations 10000 times, each with random assignments of modulation amplitude to cover the full modulation range for every source. The dependence of the detection probability on the background counts is relatively small, so the detection probability of each source is calculated mainly through an interpolation of the results from the synthetic simulations over a 2-D phase of net counts and modulation amplitude.

Fig. 11 shows the completeness simulation results, assum-
Fig. 11.— Completeness study for periodicity detection. (a) the (relative) expected distribution of the periodic sources based on the detection completeness simulation using the Z2 method. The open circles and triangles show the ten periodic sources in the LW: the latter mark the closest positions in the phase space for the sources. (b) the number of the sources with detectable periodicity as a function of the modulation. (c) the same as (b) but as a function of the net counts. (d) the same as (c) but in terms of the fractional detection. These results are for case 1 (sources with net counts greater than 50) in Table 6 and the results are shown for the three search routines.

All of the 843 sources are periodic with a uniform distribution of modulation amplitude. Fig. 11a shows the expected number of detectable sources in the 2-D phase space of net counts vs. modulation depth, based on the Z2 method as an example. Note that the absolute number of the detected sources in each cell of the phase space depends on the cell size, so what matters is relative variation from cell to cell and the total number of the detected sources. The result shows that we expect to detect 96 sources if all of the 843 sources are periodic with a uniform distribution of modulation amplitude. Since we only detected 13 periodic sources and candidates, this result indicates there should be 114 periodic sources, which is about 14% of the total source counts (see Table 6 below).

Fig. 11b and c show the number of sources with detectable periodicity as a function of modulation amplitude and net counts respectively for the three search routines. Fig. 11c also shows the given distribution of the net counts (black) for comparison. The highest probability of detection is from sources with net counts around 200 to 300. Note the sources with net counts greater than 1000 are all in the last bin of net counts. Fig. 11d shows the relative fractional detection as a function of net counts.

Table 6 summarizes the simulation results and the estimates of unidentified periodic sources among the sources found in the LW. We repeated the analysis for the three search routines and four sub-sets of the sources, which cover the cases with non-CCD-edge sources and the hard X-ray sources ($E_{50} \geq 2.5$ keV). The case using non-CCD-edge sources is informative in terms of estimating a systematic error in our selection procedure of periodic sources since the observed periodicity of the sources that fall near a CCD edge can be falsely discredited. The hard X-ray sources should be a better representative of the Bulge sources since they exclude the majority of the foreground soft sources.

The results in Table 6 agree within a few percent among the three search routines, and the estimates by non-CCD-edge sources alone come out slightly higher. They indicate that about 14–21% of the sources in the LW should be, in fact, periodic and the percentage increases to 21–31% for the hard X-ray sources. This implies a large fraction of the Bulge X-ray sources found in the GCR should be periodic, which again supports MCVs constitute the large majority of the hard X-ray Bulge sources.

Source crowding in the GCR, the large distance to the Bulge, and heavy obscuration of molecular clouds (except for the Window fields) severely limit the optical and IR followup of the GCR X-ray sources for spectral identification and further study. Therefore, in order to understand the Bulge X-ray sources in the GCR, we need to continue X-ray monitoring of the Bulge sources in the GCR for future discoveries of periodicities and unusual variability, and we also need to investigate the details of the X-ray properties of the suspected similar kind, a handful of known APs and ns-IPs to establish demo-
graphic profile of them, if any, for comparison study with the GCR sources.

6. SUMMARY

We have found 10 periodic X-ray sources and 11 candidates in the LW from the 1 MS exposure of the Chandra ACIS-I instrument. The overall period distribution, X-ray luminosity and spectral properties of these periodic sources and eight periodic sources found in the Sgr A* field (Muno et al. 2003b) fit the general description of MCVs, supporting the argument that MCVs are the major constituent of the Bulge X-ray sources. However, when inspecting the details of these X-ray properties — period distribution that resembles the polars’ and the hard X-ray spectra that resembles the IPs’ – we discover that these periodic sources may fit into a rare subclass of MCVs, nearly synchronous MCVs, some of which are considered as the missing link in the evolution of MCVs between IPs and polars. The completeness tests indicate roughly about 21–31% of the hard X-ray sources in the LW are periodic, suggesting there is a large unidentified population of MCVs in the GCR X-ray sources. Given the difficulty of identifying the nature of the Bulge X-ray sources in the GCR, we recommend continuous X-ray monitoring of the GCR for future discoveries of periodicities and unusual variabilities. Considering the importance of ns-MCVs in terms of the evolution of MCVs and their potential connection to thousands of the Bulge X-ray sources, we also encourage an in-depth systematic X-ray study of the ns-MCVs (only 13 sources with $P_{o}/P_{o} > 3$ in the RK catalog) to establish a demographic profile of their X-ray properties if any.

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REFERENCES

Casares, J., et al., 2011, ATEL #3206.
Grindlay, J. E. et al., 2011, in preparation.
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(1) The total number of sources that meet the source selection criteria. (2) The number of the detected periodic sources and candidates from Table 3. (3) The number of the periodic sources detected by simulations if all the sources are periodic with a uniform distribution of modulation amplitude. (4) The expected periodic sources: (1) / (3). (5) The percentage of periodic sources and candidates in the selection: (4)/(1).