CHANDRA DISCOVERY OF AN INTERMEDIATE POLAR IN BAADE’S WINDOW

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ABSTRACT
We have discovered an intermediate polar (IP) in the 100 ks Chandra observation of Baade’s window (BW), a low extinction region at about 4° south of the Galactic center. The source exhibits large X-ray modulations at a period of 1028.4 s in the 0.3–8 keV band. The X-ray spectral fit with a power-law model shows that the integrated spectrum is intrinsically hard (photon index $\Gamma = 0.44 \pm 0.05$) and moderately absorbed ($N_H = 1.5 \pm 1.0 \times 10^{21} {\rm cm}^{-2}$). The relatively poor statistics only allow for a mild constraint on the presence of an iron emission line (equivalent width $= 0.5 \pm 0.3$ keV at 6.7 keV). Quantile analysis reveals that the modulations in the X-ray flux strongly correlate with spectral changes that are dominated by varying internal absorption. The X-ray spectrum of the source is heavily absorbed ($N_H > 10^{22} {\rm cm}^{-2}$) during the faint phases, while the absorption is consistent with the field value ($\sim 10^{21} {\rm cm}^{-2}$) during the bright phases. These X-ray properties are typical signatures of IPs. Images taken with the IMACS camera on the Magellan 6.5 m telescope show a faint ($V \sim 22$), relatively blue object ($B_0 - V_0 \gtrsim 0.05$) within the 2σ error circle of the Chandra source, which is a good candidate for being the optical counterpart. If we assume a nominal range of absolute $V$ magnitude for a cataclysmic variable ($M_V \sim 5.5$–10.5) and the known reddening in the region ($A_V = 1.4$ at $>3$ kpc), the source would likely be at a distance of 2–10 kpc and not in the local solar neighborhood. The corresponding average X-ray luminosity would be $6 \times 10^{31} - 10^{33}$ erg s$^{-1}$ in the 2–8 keV band. Assuming the space density of IPs follows the stellar distribution, which is highly concentrated in the Galactic bulge, the source is probably a relatively bright IP ($\sim 10^{33}$ erg s$^{-1}$ if it is at 8 kpc) belonging to the Galactic bulge X-ray population, the majority of which is now believed to be magnetic cataclysmic variables.

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

Online-only material: color figures

1. INTRODUCTION

Intermediate polars (IPs) are a type of magnetic cataclysmic variable (CV) where the magnetic field of the accretor, a white dwarf (WD), disrupts the inner portion of the accretion disk and channels the accretion flow into the magnetic poles of the WD (Patterson 1998). As the WD spins, this channeling gives rise to a pulsation, a telltale sign of an IP, which is typically found in the period range of $\sim$100–1000 s. The magnetic field on the surface of the WD in IPs is typically about $10^{6}$–$10^{7}$G, and the ratio of the spin to orbital period of IPs is found in a wide range from 0.01 to <1. Some IPs are on the evolutionary path to their cousins, the polars, where the orbital and WD spin periods are usually locked under the strong magnetic fields that convert the whole accretion flow into a stream (Norton et al. 2004). Magnetic CVs provide unique astrophysical laboratories for studying physics in extreme conditions, stellar and binary evolution, which is important to make a census of Galactic population and understand their evolution. There are about 33 confirmed and 72 candidate IPs today, and the full catalog is found in Ritter & Kolb (2003).4

The 72 IP candidates contain seven periodic X-ray sources at the Galactic center (GC) which are part of $\sim$2300 X-ray sources discovered in the deep Chandra observations of the Sgr A* field (Muno et al. 2003a, 2003b). The exact nature of the majority of the GC X-ray population still remains elusive: direct identification at other wavelengths is difficult due to high obscuration by dust and source confusion due to high star density. Therefore, the discovery of these IP candidates is particularly interesting since it supports the idea of magnetic CVs as the leading candidates for the majority of the GC X-ray sources (Muno et al. 2004; Laycock et al. 2005). If true, this also implies that the GC X-ray population is very old.

In order to explore the X-ray population in the Galactic bulge (GB) without obscuration by the intervening dust, we have observed three low-extinction windows within 4° of the GC with the Chandra X-ray observatory (van den Berg et al. 2006, 2009; Hong et al. 2009). The initial population study on the X-ray sources in these windows and four GB fields has revealed that the GB X-ray sources extend out to $\sim 1.4$° from the GC with a projected source density that follows a $1/\theta$ relation, where $\theta$ is the angular offset from the GC (Hong et al. 2009). In addition, the similarity of the X-ray spectra of the hard X-ray sources in these fields—an intrinsically hard continuum with the presence of an iron emission line—indicates a single class of sources, likely magnetic CVs, could make up both the GC and GB X-ray populations.

As part of our efforts to identify the nature of these sources, we have searched for periodic modulations in the X-ray emission of the bright X-ray sources (net counts $\geq 250$ in the 0.3–8 keV range) in the window fields using the Lomb–Scargle algorithm (Scargle 1982). As a result, we have discovered an IP in Baade’s window (BW) based on a strong pulsation correlated with the X-ray spectral variation (Section 2). We explore the properties of this X-ray source (Section 3) and the potential optical counterpart (Section 4) that lead to its identification as an IP. We discuss the possibility that the system belongs to the GB X-ray population (Section 5).

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4 See the online catalog at http://physics.open.ac.uk/RKcat/ and http://asd.gsfc.nasa.gov/Koji.Mukai/iphome/iphome.html for the latest update.
2. OBSERVATION AND TIMING ANALYSIS

We have observed BW on 2003 July 9 (Obs. ID 3780), Stanek’s window (SW) on 2004 February 14/15 (Obs. ID 4547 and 5303), and limiting window (LW) on 2005 August 19/22 and October 25 (Obs. ID 5934, 6362, and 6365) with the Chandra ACIS-I instrument (van den Berg et al. 2006, 2009; Hong et al. 2009). The data were analyzed as a part of our survey program, the Chandra Multi-wavelength Plane (ChaMPlane) survey, which is designed to constrain the Galactic population of low-luminosity accretion sources, CVs in particular (Grindlay et al. 2005). In summary, we search for X-ray point sources using a wavelet algorithm (wavdetect; Freeman et al. 2002) and perform aperture photometry to extract the basic X-ray properties. The details of the analysis procedures are described in Hong et al. (2005, 2009).

In order to find periodic X-ray modulations in the light curves of these X-ray sources, we have performed a Lomb–Scargle periodicity search on the bright X-ray sources (net counts $\geq 250$ in $0.3$–$8.0$ keV) discovered in the $100$ ks observation of the window fields—BW (Obs. ID 3780), SW (Obs. ID 4547 and 5303), and LW (Obs. ID 5934, 6362, and 6365; Hong et al. 2009). The events are selected by the good time intervals (GTIs) where the background fluctuation is less than $3\sigma$ above the mean level (Hong et al. 2005). The arrival time of each photon is bary-center corrected using the CIAO tool axbary.\(^5\) For each source, we generate the light curves in time bins of four multiples (1, 4, 8, and 16) of the CCD integration time (3.2 s). Then we apply the Lomb–Scargle algorithm and calculate the power spectrum for the light curves at all four time resolutions.

We have found that one source in BW, CXOPS J180354.3-300005, exhibits a clear sign of a periodic modulation with greater than $99\%$ of the confidence level (CL). The source was detected with $510 \pm 24$ net counts in the broad band ($B_X$, $0.3$–$8$ keV) after background subtraction. Figure 1 shows the raw sky image around the source marked by the (red) circle of the $95\%$ point spread function (PSF). The source only appears to be extended due to the large offset ($8.5''$) from the aim point of the instrument, but a simulated PSF by a CIAO tool mkpsf at the source position closely resembles the event distribution of the source, indicating that the source is consistent with a point source.

Figure 2(a) shows the power spectrum of the source in the frequency domain along with horizontal lines indicating $90\%$, $95\%$, and $99\%$ CLs. This power spectrum is based on the light curve at the $12.8$ s time resolution and the results based on the other three time resolutions are very similar. The power spectrum indicates that the source exhibits pulsations at a period of $1028.4 \pm 3.8$ s. The error of the period estimate is the $1\sigma$ equivalent spread of the peak in the power spectrum, which is calculated by a fit to the peak with a Gaussian function in the period domain. The observed period is somewhat close to a possible spurious period ($1000$ s). Sources falling near the edges or node boundaries of the chips can exhibit spurious modulations at a period of $707$ or $1000$ s (or their harmonics) due to the dither motion of the Chandra X-ray observatory. However, we consider the periodic modulation found in CXOPS J180354.3-300005 to be real because, first, the source is not near the chip edges or the node boundaries and, second, the X-ray spectral properties of the source strongly correlate with the flux modulation as demonstrated below.

Figure 2(b) shows the folded light curves at the pulsation period in the soft ($0.3$–$2.0$ keV), hard ($2.0$–$8.0$ keV), and broad ($0.3$–$8.0$ keV) bands. The folded light curve of the broad band is shifted up by $1$ cts ks\(^{-1}\) for clarity. The smooth lines are calculated using the LOWESS algorithm (Cleveland 1994) and color coded by the phase for later reference in the spectral analysis (Section 3). The data points are calculated at the $10$ equal-sized phase bins of width $0.1$. The net count per bin ranges from $\sim 18$ to $90$ in the $0.3$–$8.0$ keV range.

We define the modulation depth as $(R_{\text{max}} - R_{\text{min}})/(R_{\text{max}} + R_{\text{min}})$ where $R_{\text{max}}$ and $R_{\text{min}}$ are the maximum and minimum of the fitted amplitudes, respectively. Using a fit to the $10$ data points with a sinusoidal function, we estimate that the modulation depth is $(90 \pm 10)\%$, $(42 \pm 10)\%$, and $(53 \pm 8)\%$ for the soft, hard, and broad bands, respectively. The modulation amplitude varies with the energy band, which we will explore in more detail using quantile analysis in Section 3.

BW was also observed with the EPIC cameras on the XMM-Newton observatory in two separate pointings with $\sim 20$–$25$ ks exposure each on 2002 March 11 and 2004 September 30. The data from both observations are publicly available. Our source was detected as 2XMM J180354.3-300004\(^6\) at large offsets ($5.7$ and $7.6$) from the aim point in both observations (Watson et al. 2009). Unfortunately, in four data sets out of the total six (three cameras and two pointings) the source fell near a chip gap. In both PN observations, which would have provided an interesting result because of the superior sensitivity at high energies to the Chandra ACIS instruments, the central part of the PSF overlapped with a chip gap, rendering the data practically unusable. Three MOS observations (including one with the source marginally close ($\sim 30''$) to the chip edge) appear to produce a relatively clean data set of the source, but the poor statistics (net counts: $\sim 60$–$80$ each in $0.3$–$8$ keV) did not allow for any significant detection of pulsation. Therefore, in the following, we mainly consider the Chandra data for the X-ray observation of the source. See Table 1 for the overall flux estimates of the source from the XMM-Newton observations, which are consistent with those from the Chandra data.

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\(^5\) http://cxc.harvard.edu.

\(^6\) http://xmm.esac.esa.int/xsa/.

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Figure 1. The raw X-ray sky image around CXOPS J180354.3-300005. The (red) circle indicates the source region used for the aperture photometry. The morphology of the event distribution is consistent with the expected PSF at the source location.

(A color version of this figure is available in the online journal.)
low statistics and lack of spectral information at high energies cannot confirm this apparent high temperature is intrinsic due to hard, and broad bands, respectively. The folded light curves in the broad band are shifted up by 1 cts ks line at 6.7 keV is 0.5 iron line. The estimated equivalent width (EW) of the iron do not provide a significant constraint on the presence of the 6 – 7 keV energy range in the spectrum but the poor statistics plus the iron line. There is a hint of an emission line in the to the integrated spectrum of the source using the power law

\[ N_{H22} = (2.0–8.0 \text{ keV}) \text{ and broad bands (phase = 0 at JD 2452830.0). The primary modulation is found at } 9.727 \pm 0.036 \times 10^{-4} \text{ Hz or } 1028.4 \pm 3.8 \text{ s. The horizontal lines in } (a) \text{ represent the CLs of 90\%, 95\%, and 99\%. The smooth lines in } (b) \text{ are generated by the LOWESS algorithm and color coded by the phase for later referenc e (Figure 4). The data points are calculated in the equal phase bins (0.1). The modulation depth is estimated to be } (90 \pm 0.3 \text{ keV). In the case of the thermal modulation phase, we use quantile analysis. Quantile analysis provides a reliable spectral measure of sources or for investigating subsets of the data that do not allow the conventional hardness ratio, which is subject to the spectral bias intrinsic to the choice of the sub-energy ranges, quantile analysis provides a reliable spectral measure of sources even with counts as low as } \sim 10 \text{ because it takes full advantage of the given statistics without sub-dividing the energy range (e.g., van den Berg et al. 2006).}

We calculate the quantile values of the X-ray spectra of the source as a function of modulation phase using a sliding phase

**Figure 2.** The power spectrum (a) of CXOPS J180354.3-300005 in the broad band (0.3–8.0 keV) and the folded light curves (b) in the soft (0.3–2.0 keV), hard (2.0–8.0 keV), and broad bands (phase = 0 at JD 2452830.0). The primary modulation is found at 9.727 ± 0.036 × 10^{-4} Hz or 1028.4 ± 3.8 s. The horizontal lines in (a) represent the CLs of 90\%, 95\%, and 99\%. The smooth lines in (b) are generated by the LOWESS algorithm and color coded by the phase for later referenc e (Figure 4). The data points are calculated in the equal phase bins (0.1). The modulation depth is estimated to be (90 \pm 0.3 \text{ keV). In the case of the thermal modulation phase, we use quantile analysis. Quantile analysis provides a reliable spectral measure of sources or for investigating subsets of the data that do not allow the conventional hardness ratio, which is subject to the spectral bias intrinsic to the choice of the sub-energy ranges, quantile analysis provides a reliable spectral measure of sources even with counts as low as } \sim 10 \text{ because it takes full advantage of the given statistics without sub-dividing the energy range (e.g., van den Berg et al. 2006). We calculate the quantile values of the X-ray spectra of the source as a function of modulation phase using a sliding phase

| Spectral Fits | Quantile Analysis | Flux |
|---------------|------------------|------|
| Model         | \( N_{H22} \) (\( \times 10^{22} \text{ cm}^{-2} \)) | \( \Gamma \) | \( \text{EW (keV)} \) | \( \chi^2/\text{dof} \) | \( N_{H22} \) (\( \times 10^{22} \text{ cm}^{-2} \)) | \( \Gamma \) | \( \text{EW (keV)} \) | \( 0.5–2 \text{ keV} \) | \( 2–8 \text{ keV} \) | \( \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \) |
| Chandra PL    | 0.15(10)         | 0.44(5) | ... | 12.6/22 | 0.28(21) | 0.49(18) | ... | 0.13(1) | 1.20(7) |
| Chandra PL+Fe | 0.22(10)         | 0.53(5) | 0.5(3) | 10.3/20 | 0.39(22) | 0.63(18) | 0.5 | 0.14(1) | 1.19(7) |
| XMM-Newton MOS PL | 0.61(0.64) | 0.60(0.41) | 0.39(0.39) | ... | 0.19(12) | 1.25(43) |

Notes. For the Chandra data, the flux estimates are based on the spectral model fits. The errors are of statistical origin, based on the photon counts using small-number statistics by Gehrels et al. (1986). The PL+Fe model in the quantile analysis assumes a 0.5 keV EW for the iron line at 6.7 keV. In the XMM-Newton data, we combine three data sets and use quantile analyses under a simple power law. The data sets comprise the MOS1 observation in the 2002 pointing, and both the MOS1 & MOS2 observations in 2004. The flux estimate is based on the quantile analysis of the combined data set, and the errors are the quadratic sum of the statistical error and the standard deviation of the three data sets. The reported flux in 0.2–12 keV is 1.9(2) \times 10^{-13} and 1.6(2) \times 10^{-13} erg cm^{-2} s^{-1} for the 2002 and 2004 XMM-Newton observations, respectively (Watson et al. 2009; see also http://xmm.esac.esa.int/xsa/). doF stands for degrees of freedom.

3. X-RAY SPECTRUM AND VARIATION

Table 1 summarizes the results of the spectral model fits to the integrated X-ray spectrum of the source using a power-law model with and without an iron emission line at 6.7 keV. The Fe He\( ^{α} \) XXV line is considered because many of the GC X-ray sources exhibit this line more prominently than the neutral Fe He line at 6.4 keV (Wang et al. 2002; Munu et al. 2003a; Hong et al. 2009). Both models produce acceptable fits, and the spectrum is intrinsically hard (\( \Gamma \sim 0.4 \)) and moderately absorbed (\( N_{H22} \sim 0.2 \)). Figure 3 shows the spectral model fit to the integrated spectrum of the source using the power law plus the iron line. There is a hint of an emission line in the 6 – 7 keV energy range in the spectrum but the poor statistics do not provide a significant constraint on the presence of the iron line. The estimated equivalent width (EW) of the iron line at 6.7 keV is 0.5 ± 0.3 keV. In the case of the thermal bremsstrahlung or thermal plasma model, we can only assign a lower limit for the temperature (\( >10 \text{ keV} \)) with 95\% CL for thermal bremsstrahlung or \( >7.0 \text{ keV} \) for MeKaL and we cannot confirm this apparent high temperature is intrinsic due to low statistics and lack of spectral information at high energies (\( >10 \text{ keV} \)).

The total column density in the direction of CXOPS J180354.3-300005 is estimated to be \( N_{H22} = 0.25(8) \) by Marshall et al. (2006) or 0.25(5) by Sumi (2004), using \( N_{H22} = 0.179 \text{ A}_V \) (Predehl & Schmitt 1995). The former estimates are given in a set of distances starting from 2.75 kpc for the BW field and the latter estimates are given at a finer angular resolution (\( \sim 0.5–2.0' \)) than the former (\( \sim 8.0' \)). There are also other estimates for the extinction in the BW such as \( \sim 0.34 \) by Schlegel et al. (1998) or \( \sim 0.41 \) by Drimmel et al. (2003), but the underlying models of these estimates are not accurate in this region.

In order to explore the spectral variation as a function of the modulation phase, we use quantile analysis. Quantile analysis is a bias-free spectral classification method, suitable for faint sources or for investigating subsets of the data that do not allow for spectral model fits due to low statistics (Hong et al. 2004). Unlike the conventional hardness ratio, which is subject to the spectral bias intrinsic to the choice of the sub-energy ranges, quantile analysis provides a reliable spectral measure of sources even with counts as low as \( \sim 10 \) because it takes full advantage of the given statistics without sub-dividing the energy range (e.g., van den Berg et al. 2006).

We calculate the quantile values of the X-ray spectra of the source as a function of modulation phase using a sliding phase
Figure 3. The spectral model fit to the integrated X-ray spectrum of CXOPS J180354.3-300005 under a power law plus an iron line at 6.7 keV. See also Table 1. The spectral fit shows a hint of the iron emission line. (A color version of this figure is available in the online journal.)

window of a fixed size (0.1). Figure 4 shows such a quantile diagram. The energy quantile $E_p$ corresponds to the energy below which $p\%$ of the counts are detected in the energy range (0.3–8.0 keV in Figure 4). For instance, $E_{50}$ means the median energy, and $E_{25}$ and $E_{75}$ are two quartiles. Note that the definition of the x-axis in Figure 4 is different from the one suggested by Hong et al. (2004). The new definition is $\log_{10}(E_{50}/E_{lo})/\log_{10}(E_{hi}/E_{lo})$ in general, where $E_{lo}$ and $E_{hi}$ are the lower and upper bound of the energy range, respectively ($E_{lo} = 0.3$ and $E_{hi} = 8.0$ keV in Figure 4). We believe that the new definition is more reflective of the instrument response and the confined range (0–1) allows for a statistically more uniform response throughout the phase space of quantile diagram (J. Hong et al. 2009, in preparation).

For easy interpretation, the quantile diagram is overlaid with power-law and thermal bremsstrahlung model grids. The filled circles are color coded to match the phase of the smooth line in the folded light curve in Figure 2(b) for easy comparison and the data points with the error bars are from the same 10 data points in the folded light curve. Table 1 also shows the spectral parameters estimated by quantile analysis of the integrated spectrum (marked by a hollow cross in Figure 4) and the results are consistent with the spectral fit.

The quantile diagram reveals dramatic spectral changes as a function of pulsation phase, illustrated by a large loop formed counter-clockwise as the X-ray flux modulates in a full cycle (see the track in Figure 4(b)). The spectral variation is expected from the energy dependence of the modulation depth seen in Figure 2. In the quantile diagram, we can also see that the spectral changes are dominated by varying extinction. During the bright phases, the spectrum is relatively unabsorbed with $N_{H2} < 1$, less than or consistent with the field extinction (e.g., the yellow and red points in Figures 2(b) and 4(b)), but during the faint phases, especially around phases 0.3–0.6 (e.g., the light blue points), the spectrum is heavily absorbed with $N_{H2} > 5$. Since the field extinction is very low, the additional increase in extinction must be intrinsic to the source. Note that the long axis of the data loop in the quantile diagram is largely parallel to the direction related to changes in absorption for both spectral models as shown in Figure 4. In fact, this is true in general regardless of the spectral models.

Table 1 also shows the results of the XMM-Newton data for comparison, for which we combine three relatively clean data sets (the MOS1 observation in 2002, both MOS1 and MOS2 in 2004). The overall spectral properties and the flux estimates of the XMM-Newton data based on the quantile analysis are consistent with those derived from the Chandra data.

4. OPTICAL COUNTERPART

On 2007 May 8, we observed the three window fields with the Inamori Magellan Areal Camera and Spectrograph (IMACS) on...
the 6.5 m Magellan (Baade) telescope at Las Campanas, Chile. Under good conditions (seeing FWHM \( \sim 0.5' \), clear sky) we obtained a dithered set of five pointings in the \( f/4 \) configuration (15' field, 0.2' pixel) to cover an 18' \( \times \) 18' region of the BW. This provided a total exposure time of 500 s in each of Bessell-\( B \), \( V \), \( R \), and CTIO-\( I \) filters over the Chandra field.

We processed the images using standard IRAF tasks, and calibrated the astrometry using the Two Micron All Sky Survey (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\(^7\) utility. All frames were normalized to ADU/second units and combined using weight maps constructed from flat fields and bad pixel masks. The initial source search and photometry were performed on the stacked images using SExtractor (Bertin & Arnouts 1996).

After boresighting the initial IMACS source list to the Chandra sources (Zhao et al. 2005), and applying offsets of \( \Delta \text{RA} = 0.088(51) '' \), \( \Delta \text{DEC} = 0.498(50) '' \) to the X-ray coordinates, we found a potential counterpart in the \( B \)- and \( V \)-band images within the search area of the Chandra source. In Figure 5(a), the source search area is marked by the (red) circle, the radius of which is the 2\( \sigma \) quadratic sum of the boresight error and the positional errors of the X-ray and optical sources (Zhao et al. 2005). The potential counterpart (indicated with green tick marks in the figure) is not completely resolved with a nearby star (orange). Therefore, we generate a PSF model using a few marks in the figure) is not completely resolved with a nearby star (orange). Therefore, we generate a PSF model using a few marks in the figure) is not completely resolved with a nearby star (orange). Therefore, we generate a PSF model using a few marks in the figure. The candidate counterpart and the neighbor star are marked by green and orange tick marks respectively (white tick marks for the print edition). The CMD compares the two marked sources with the field stars within 30'. The potential counterpart (green diamond) is mildly bluer than the most field stars.

(A color version of this figure is available in the online journal.)

Figure 5. The finding chart in the \( B-V \), \( I-V \), and \( R-B \)-band images (left) and the CMD in \( B \) vs. \( B-V \) (right). In the finding chart the (red) circle centered at the X-ray source (radius: 2\( \sigma \) of the composite errors, 0.66) indicates the search region for counterparts. The candidate counterpart and the neighbor star are marked by green and orange tick marks respectively (white tick marks for the print edition). The CMD compares the two marked sources with the field stars within 30'. The potential counterpart (green diamond) is mildly bluer than the most field stars.

Figure 5(b) shows a calibrated color–magnitude diagram (CMD) for stars within \( \sim 30' \) of the potential counterpart (green diamond) and the neighbor (orange square). The CMD shows that the potential counterpart is bluer than the majority of field stars. The calibrated apparent magnitude of the optical counterpart is \( B = 22.2(1) \), \( V = 21.7(1) \), and \( I = 20.6(1) \) where the errors are the output of the DAOPHOT. Taking the interstellar extinction to BW to be \( A_V = 0.14 \), \( E(B-V) = 0-0.45 \) leads to a dereddened color index \( B-V_0 = 0.05-0.5 \) for the optical counterpart. This value is in the typical range for cataclysmic variables—see, for example, Allen (1977), table 17.9. The number of blue sources (24 sources with \( B-V < 0.7 \)) falling in the error circle by chance is about 0.03.

We estimate the ratio of the unabsorbed X-ray to optical flux, \( \log(F_X/F_V) = 0.63-1.12 \) for \( A_V = 0.0-1.4 \), where \( F_X \) is in the 2–8 keV range. The blue color of the optical source and the relatively high value of \( 
\log(F_X/F_V) \) (typically \( < -2.5 \) for normal stars) are consistent with the accretion nature of the X-ray emission from the source, indicating that the optical source is a good candidate for being the counterpart.

5. DISCUSSION

The lack of a bright optical counterpart (\( V \lesssim 14 \)) rules out a high-mass X-ray binary (HMXB) and hence a neutron star pulsar for the system. The relatively hard spectrum rules out a quiescent low-mass X-ray binary or a coronal nature of the X-ray emission. In fact, the X-ray properties of the source show classic signatures of IPs such as the intrinsically hard X-ray spectrum with, although marginal, a possible iron emission line and the X-ray pulsation correlated with the internal absorption at a period of 1028 s. The estimated luminosity of the system (see below) is also consistent with IPs. A likely scenario for modulating internal absorption at the spin period is that in a bright phase we have a relatively uninterrupted view of the emission region on the surface of the WD whereas in a faint phase we are looking at the emission region through the channeled accretion stream, which attenuates the X-rays.

In the following, we estimate the likely distance of the source to see if the system could belong to the GB population, the
majority of which are believed to be IPs. If we assume a typical range of absolute $V$ magnitude for a CV ($M_V \sim 5.5$–10.5; Patterson 1998) and the known reddening in the region ($A_V = 1.4$ at $>3$ kpc; Marshall et al. 2006), the source distance should be in the range of 2–10 kpc for $V \sim 22$, suggesting that the source is nonlocal. Note if this optical source is not the counterpart of the X-ray source ($V \sim 22$), the distance estimate becomes the lower bound, which reinforces the argument that the X-ray source is nonlocal. The corresponding average X-ray luminosity would be $6 \times 10^{31} - 10^{33}$ erg $s^{-1}$ in the 2–8 keV range. According to the population synthesis model for the magnetic CVs in the GC region by Ruiter et al. (2006) and Heinke et al. (2008), this luminosity range is acceptable for magnetic CVs.

We can take this a step further. Assuming the space density of IPs follows the stellar density, in BW we expect IPs are more likely found in the GB at 8 kpc, which allows for a direct detection of modulations. For instance, if the source was located in the GC in the Sgr A* field (Baganoff et al. 2003) if the source was located in the GC in the Sgr A* field. Note indeed there are numerous IPs among the hard X-ray sources found in this region, long-term X-ray monitoring can lead to a direct identification of many sources through detection of pulsations. For instance, if 1 Ms exposure of the BW, we expect to detect $>500$ counts from IPs with $10^{32}$ erg $s^{-1}$ in the GB at 8 kpc, which allows for a direct detection of modulations if present. A crude scaling using $N(S) \sim S^{-1.5}$ predicts we should be able to identify $\sim30$ sources or more in BW from such an exposure, and at $10^{32}$ erg $s^{-1}$ or below, we start to see the major part of the luminosity distribution of the magnetic CVs according to Ruiter et al. (2006) and Heinke et al. (2008).

In addition, low-extinction regions such as the window fields are better suited for this approach than high-extinction fields such as Sgr A* since the dust in the high-extinction fields would attenuate the apparent X-ray modulation or spectral changes dramatically, which would make the pulsation very hard to detect. For example, the spectral variation seen in Figure 4 would not have been easily identifiable with the substantial external extinction ($N_H \sim 6$, a nominal value for the GC (Baganoff et al. 2003)) if the source was located in the GC in the Sgr A* field.

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Figure 6. The combined probability distribution of the source distance (black circles) from the stellar distribution (red squares, model A in Hong et al. (2009)) and the distance distribution based on the X-ray luminosity (blue diamonds, the standard model in Ruiter et al. (2006)) for the given flux of the source ($1.2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$). The unshaded region represents the acceptable distance for the source based on the $V$ magnitude of the potential counterpart. Each distribution is rebinned in 0.5 kpc intervals.

(A color version of this figure is available in the online journal.)