DETECTION OF X-RAY PERIODICITY FROM A NEW ECLIPSING POLAR CANDIDATE XGPS-I J183251-100106

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ABSTRACT

We report the results from a detailed analysis of an archival XMM-Newton observation of the X-ray source XGPS-I J183251-100106, which has been suggested as a promising magnetic cataclysmic variable (CV) candidate based on its optical properties. A single periodic signal of $\sim1.5$ hr is detected from all EPIC instruments on board XMM-Newton. The phase-averaged X-ray spectrum can be well modeled with a thermal bremsstrahlung temperature of $kT \sim 50$ keV. Both the X-ray spectral and temporal behavior of this system suggest that it is an eclipsing CV of the AM Herculis (or polar) type.

Key words: stars: individual (XGPS-I J183251-100106, 2XMM J183251.4-100106) – X-rays: stars

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1. INTRODUCTION

The XMM-Newton Galactic Plane Survey (XGPS) has revealed a large population of X-ray sources (Hands et al. 2004). In order to identify the nature of the brightest sources detected in XGPS, an optical campaign has recently been carried out (Motch et al. 2010). In this process, three sources were identified as promising cataclysmic variables (CVs).

The X-ray source designated as XGPS-9 (=XGPS-I J183251-100106) in Motch et al. (2010) is one of the newly found CV candidates in XGPS. Two optical objects are found within its X-ray error circle; the fainter one ($V \sim 23.3$) is suggested to be the companion counterpart. Its CV nature was identified through optical spectroscopy, which unambiguously shows strong H, He i, and He ii emission along with a blue continuum (Motch et al. 2010). These features are known to be typical for a magnetic CV.

Apart from the optical identification, Motch et al. (2010) have also reported a brief X-ray analysis of archival XMM-Newton data obtained by the observations on 2002 March 15 (ObsIDs 0135741601, 0135744401). The authors found that an absorbed single-component thermal plasma model is able to describe the data. However, as XGPS-9 is located at an off-axis angle $\sim8$ ks and $\sim5$ ks, respectively), the poor statistics and the degraded angular resolution leave the spectral parameters unconstrained. While the X-ray light curve of XGPS-9 (Figure 8 in Motch et al. 2010) clearly shows the variability of this source, these short observations preclude the search for any periodic behavior in this system.

In order to tightly constrain its X-ray properties, we have performed a follow-up investigation of XGPS-9 with a deep XMM-Newton observation. The results of this analysis are presented in this paper.

2. OBSERVATION AND DATA ANALYSIS

XGPS-9 was observed by the European Photon Imaging Camera (EPIC) on board XMM-Newton, which consists of two metal oxide semiconductor CCD detectors (MOS1 and MOS2) and a PN CCD detector, on 2009 October 8–9 (ObsID 0605480101). While the MOS1/2 cameras were operated in full frame mode with a temporal resolution of 2.6 s, the PN camera was operated in the extended full frame mode with a temporal resolution of 199.1 ms. Medium filters were used to block optical stray light in all EPIC instruments.

The aim point of this observation is R.A. = 18$^h$32$^m$57$^s$.01, decl. = $-10^\circ$05'41''0 (J2000). Using tasks emproc and epproc of the XMM Science Analysis Software (XMMSAS version 11.0.0), we have reprocessed all the EPIC data with the updated instrumental calibration. We subsequently selected only those events for which the pattern was between 0 and 12 for both MOS cameras and 0–4 for the PN camera in 0.3–12 keV. We further cleaned the data by accepting only the good times when the sky background was low for the whole camera (<2.4 counts s$^{-1}$, <2.8 counts s$^{-1}$, and <5.7 counts s$^{-1}$ for MOS1, MOS2, and PN, respectively). After removing all events which were potentially contaminated by bad pixels, the effective exposures were found to be 55.9 ks, 56.6 ks, and 41.3 ks for MOS1, MOS2, and PN, respectively.

We also utilized the optical monitor (OM) data for our investigation. XGPS-9 was observed by OM in standard imaging mode with three different filters: U (effective wavelength 3440 Å), UVW1 (2910 Å), and UVM2 (2310 Å). The exposures of OM with U, UVW1, and UVM2 were 4.4 ks, 4.4 ks, and 2.5 ks, respectively. For data reprocessing, flat fielding and instrumental calibration. We subsequently selected only those events for which the pattern was between 0 and 12 for both MOS cameras and 0–4 for the PN camera in 0.3–12 keV. We further cleaned the data by accepting only the good times when the sky background was low for the whole camera (<2.4 counts s$^{-1}$, <2.8 counts s$^{-1}$, and <5.7 counts s$^{-1}$ for MOS1, MOS2, and PN, respectively). After removing all events which were potentially contaminated by bad pixels, the effective exposures were found to be 55.9 ks, 56.6 ks, and 41.3 ks for MOS1, MOS2, and PN, respectively.

This observation was originally intended for a spectro-imaging investigation of the supernova remnant Kes 69 (see Figure 1), which has poorly constrained X-ray properties (see Yusef-Zadeh et al. 2003; Bocchino et al. 2012). A detailed analysis of the remnant emission from Kes 69 will be published elsewhere (K. A. Seo et al., in preparation) as this falls out of the scope of this paper. In this observation, XGPS-9 is a serendipitous source located at an off-axis angle of $\sim5^\circ$ (Figure 1). With the aid of the XMMSAS task edetect_chain, we have run the source detection individually on each EPIC data set. The mean X-ray position of XGPS-9 determined from this observation is R.A. = 18$^h$32$^m$51.51, decl. = $-10^\circ$01'05'0 (J2000), with a resultant uncertainty of 0.44 by combining the statistical errors inferred from each camera in quadrature. This X-ray position is marked as a black cross in Figure 1.
Figure 1. X-ray image of an 18′ × 18′ field of view toward the supernova remnant Kes 69 with the MOS1/2 and PN data merged. XGPS-I J183251-100106 is the bright serendipitous source marked by a black cross. The dashed circle represents the background region adopted for the spectral analysis (see the text).

For the timing analysis, the point source was extracted within a circular region of radius 15″ centered at the X-ray position from each camera, which corresponds to an encircled energy fraction of ∼70%. A total of 758 counts, 682 counts, and 1277 counts were obtained from MOS1, MOS2, and PN, respectively. All the photon arrival times are subsequently corrected to the solar system barycenter with the XMMSAS tool *barycen* by adopting the updated ephemeris JPL DE405 and the aforementioned mean X-ray position.

In order to search for periodicity, we have applied the techniques of epoch folding and the Lomb–Scargle periodogram (Scargle 1982) on the event list and the binned light curve, respectively. The epoch-folding method was performed with the *efsearch* subpackage of HEAsoft. The peak value of the χ² spectrum with 50 bins for the arrival time of merged MOS and PN events is at $P = 5337.7 \pm 11.7$ s. The uncertainty of epoch folding is estimated according to the empirical formula of Leahy (1987). On the other hand, we have binned all of the events into a light curve with 150 s resolution to calculate the Lomb–Scargle periodogram. The periodogram demonstrates a periodicity of $P = 5353.0 \pm 13.5$ s which is consistent with the result of epoch folding. The uncertainty was estimated by $10^4$ times of Monte Carlo simulation. The results of the periodicity search using the epoch-folding and Lomb–Scargle methods are shown in Figure 2.

In order to identify the nature of this periodicity, we have also folded the photon events based upon the period we detected. The 5337.7 s period was adopted to fold the light curve, as it is a direct result of the epoch folding. In addition, we have divided the photons into a soft band (0.3–2.5 keV) and a hard band (2.5–12 keV) for computing the hardness ratio: (hard−soft)/(hard+soft). The folded light curves of both bands and the hardness ratio are shown in Figure 3, where the zero epoch is set at MJD 55113.0383.

The minimum at zero phase is particularly interesting and leads us to investigate it further. This feature resembles those which resulted from the eclipses of the X-ray emitting regions in the polars (e.g., Mukai et al. 2003; Vogel et al. 2008). We note that there is residual X-ray emission at the minimum. To investigate if the residual is caused by the background, we estimated the count rates within a number of source-free circular regions of 15″ radius around XGPS-9. The average background count rate estimated from the merged data set is $(3 \pm 2) \times 10^{-3}$ counts s$^{-1}$, which is consistent with the minimum

4 We note that when we compared DE200, the previous generation of planetary ephemeris, with DE405, there was a ∼300 m error in Earth’s position. This corresponds to a timing error of ∼1 μs, which is negligible in our investigation of orbital period.
of the folded light curve in 0.3–12 keV. This suggests that the residual X-rays are likely the background contamination. Therefore, the feature may be a total eclipse of the X-ray emitting region by the companion star.

To further characterize this feature, we attempted to estimate the eclipse width and to obtain an ephemeris. In view of the relatively low statistics, these properties cannot be properly constrained by fitting the eclipse profile. Instead, visual inspection was adopted for the measurements reported in this paper. The folded light curves shown in Figure 3 suggest that the ingress and egress are rather sharp, which allow us to estimate the eclipse duration with a flat bottom minimum. This leads to an approximate width of 320 ± 53 s, where the uncertainty is estimated from half of the bin size in Figure 3.

For defining the mid-eclipse phase, we adopted the mid-point of this feature in Figure 3. The timing of the X-ray eclipse can
be described by the following linear ephemeris:

\[ T_{\text{N(mid-eclipse)}} = \text{MJD(TDB)}(55113.0383 \pm 6.2 \times 10^{-4}) + \frac{5337.7 \pm 21.7}{86400} \times N. \]  

We have also checked these results by adopting different bin sizes (32, 64, 128 bins/period). We found that both the eclipse width and the ephemeris are consistent with the aforementioned results within the tolerance of uncertainties.

To investigate if the periodic signal comes from the synchronized rotation, we further examined the existence of any marginal periodic signal in a larger frequency range using the \( \chi^2 \) test with 32 bins and a Fourier resolution. Because the spin period of a typical white dwarf is of order hundreds of seconds (cf. Ritter & Kolb 2003), and the signal of orbital modulation seriously contaminates the periodogram when the searching range is larger than \( 2.5 \times 10^{-3} \text{ s}^{-1} \), we only considered a periodic signal of spin within 100–400 s. Within this selected range, the largest peak value can be found at 164.7(1) s with the chance probability of \( 9.6 \times 10^{-5} \). However, this result is not significant if we take into account the number of trials in the searching range. We also tried decomposition methods (e.g., the empirical mode decomposition proposed by Huang et al. 1998) to resolve another strong signal. However, these did not yield any other periodicity except for the binary modulation. Therefore, we conclude that no spin period can be detected from the current observation, which may give us some insight into the synchronized spin and orbital periods.

Motch et al. (2010) have briefly reported the X-ray spectrum of XGPS-9. They found that a one-component thermal plasma spectrum with a column absorption of \( N_H \sim 8 \times 10^{21} \text{ cm}^{-2} \) can provide a reasonable fit to the data. However, due to the limited photon statistics, the plasma temperature and the X-ray flux in their study remain unconstrained. With a much longer integration time for the data adopted in our investigation, we are able to provide a tighter constraint on the spectral properties. For the spectral analysis, we have extracted the spectrum within a circular region of radius 30” in each MOS camera and radius 25” in the PN camera around the X-ray position, respectively. This corresponds to an encircled energy fraction of \( \sim 85\% \) in all EPIC instruments. Spectra extracted from each camera were grouped so as to have at least 50 counts per spectral bin. The background spectra were sampled from the low-count circular region of radius 30” centered at R.A. = 18\(^\text{h}\)32\(^{\text{m}}\)55\(^{\text{s}}\)72, decl. = \(-10^\circ02'05''37\) (J2000) in each camera. Response files were computed by using the XMM-SAS tasks rmfgen and arfgen. For the spectral analysis, we used XSPEC (version 12.6.0) with \( \chi^2 \) statistics adopted for all the fittings. The quoted uncertainties of the spectral parameters are 1\( \sigma \) for each parameter of interest.

Based on the optical properties, Motch et al. (2010) suggested that XGPS-9 is a magnetic CV. To explore this scenario, we examine its X-ray spectrum by fitting an absorbed thermal bremsstrahlung model, which accounts for the X-ray emission from the shock-heated gas in the accretion column. We found that this single-component model can describe the data reasonably well with a goodness of fit of \( \chi^2 = 49.40 \) for 54 dof. The spectral fit yields a column density of \( N_H = 7.6^{+0.8}_{-0.5} \times 10^{21} \text{ cm}^{-2} \), a plasma temperature of \( kT = 46 \pm 10 \text{ keV} \), and an unabsorbed flux of \( f_x = 3.3^{+0.9}_{-0.2} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \) in the energy range 0.3–10 keV. The comparison between the best-fit model and the data is shown in Figure 4. We have also computed the confidence contours to investigate the relative parameter dependence between the plasma temperature and the column absorption; these are plotted in Figure 5.

As X-ray spectra of CVs may show the presence of line emission, we have also examined the observed spectrum of XGPS-9 with XSPEC model MEKAL which is a code that models the plasma in collisional ionization equilibrium with the line emission built in. We found that the fit yields a comparable goodness of fit to the thermal bremsstrahlung model.

**Figure 4.** Energy spectrum of XGPS-I J183251–100106 as observed with the PN (upper spectra) and MOS1/2 detectors (lower spectra) and simultaneously fitted to an absorbed thermal bremsstrahlung model (upper panel) and the contribution to the \( \chi^2 \) fit statistic (lower panel).
\( \chi^2 = 50.11 \) for 54 dof. The best-fit spectral parameters are also similar \( (N_d = 7.5 \pm 0.7 \times 10^{21} \text{ cm}^{-2}, kT = 50^{+13}_{-11} \text{ keV}) \).

For the magnetic CVs, part of the thermal bremsstrahlung emission may be Compton reflected by the white dwarf surface (see Matt et al. 1998). This so-called Compton reflection component is expected to be accompanied by a fluorescent Ke iron line (de Martino et al. 2008). In order to search for evidence of the line feature, we have added a Gaussian component to the thermal bremsstrahlung model and fixed the line energy at 6.4 keV. Initially, we allowed both the normalization and the line width as free parameters. However, we found that the line width cannot be constrained (i.e., the fitted width is essentially zero). This led us to fix the line width at a reasonable value of \( \sigma = 100 \text{ eV} \) (see Balman 2011; de Martino et al. 2008). This results in best-fit parameters of \( N_d = 7.8^{+0.9}_{-0.8} \times 10^{21} \text{ cm}^{-2}, kT = 36 \pm 10 \text{ keV} \), and a line flux of \( f_{6.4 \text{ keV}} = 3.0^{+4.5}_{-3.0} \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1} \) with \( \chi^2 = 49.11 \) for 53 dof in view of the large uncertainty on the fitted line flux and the insignificant improvement of the goodness of fit, we conclude that there is no compelling evidence for the Fe K\alpha line in this observation. We report a 1\sigma upper limit on the line flux of \( f_{6.4 \text{ keV}} < 7.5 \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1} \).

While the thermal bremsstrahlung/MEKAL method can model the spectrum well, as mentioned by Motch et al. (2010), the spectral hardening may be a result of the reflection component and/or warm absorption (see Schwarz et al. 2009; Staude et al. 2008). Therefore, the plasma temperature inferred from this simple model can be unphysically high. We also investigated if any other single-component model can provide any acceptable phenomenological description. We note that a simple absorbed power law can also result in a comparable goodness of fit \( (\chi^2 = 49.83 \) for 54 dof), and hence we cannot distinguish it statistically from the thermal bremsstrahlung/MEKAL model. The power-law spectral fit yields \( N_d = 7.9^{+1.3}_{-0.9} \times 10^{21} \text{ cm}^{-2}, \) a photon index of \( \Gamma = 1.3 \pm 0.1 \), and an unabsorbed flux of \( f_x = 3.4^{+0.9}_{-0.7} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \) (0.3–10 keV). The spectral steepness and the flux are fully consistent with those inferred from a brief analysis limited to the hard band (i.e., 3–10 keV), as reported recently (cf. Table 1 in Bocchino et al. 2012).

We checked the robustness of all the spectral results quoted in this paper by incorporating the background spectra sampled from different source-free regions around XGPS-9. We found that the spectral parameters inferred from the fits with different adopted backgrounds are consistent within 1\sigma uncertainties.

We have also attempted to constrain the possible contribution from the soft component by using OM data. The soft component from a CV can originate from the optically thick blackbody-like emission of the white dwarf surface. The temperature can range from a few tens to hundreds of eV (Evans & Hellier 2007). Searching for the optical/UV counterpart in the OM data results in non-detection in all three bands, which places a limiting flux density of \(<2.3 \mu \text{Jy}, <2.7 \mu \text{Jy}, \text{ and } <7.8 \mu \text{Jy}\) in U, UVW1, and UVM2, respectively. We adopted the column density inferred from the X-ray spectral fitting (i.e., \( 7.5 \times 10^{21} \text{ cm}^{-2} \)) to perform the extinction correction (cf. Predel & Schmitt 1995; Cardelli et al. 1989). With the de-reddened limiting flux densities, we place an upper bound for any soft component contribution by assuming a low-temperature white dwarf with \( kT = 10 \text{ keV} \) (see Figure 6). The blackbody gives a limiting flux of \(<5.4 \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1} \) in 0.3–10 keV, which is \(<0.002\%\) of the total X-ray flux in this energy range.

3. SUMMARY AND DISCUSSION

Utilizing archival XMM-Newton data, we detected the periodicity from a new CV candidate XGPS-9. Through a detailed timing analysis, only a single periodic signal of \(~1.5 \text{ hr}\) can be found. This suggests a possible scenario of synchronous
Figure 6. Dashed line represents the upper bound of possible blackbody contribution at $kT = 10 \text{eV}$, as constrained by the extinction-corrected limiting flux densities deduced from the OM data (triangular symbols).

rotation, which favors the interpretation that the system is a magnetic CV of polar type.

For a polar, the white dwarf is accreting matter from its late-type main-sequence companion via Roche lobe overflow, which will be driven by the strong magnetic field of the white dwarf (with a surface magnetic field strength of few tens of millions of Gauss) to form a quasi-radial flow toward the magnetic pole. The accretion flow will eventually form a strong shock above the stellar surface. The shock-heated plasma will be cooled via bremsstrahlung radiation in the X-ray regime with a typical temperature of few tens of keV, which is consistent with the best-fit plasma temperature (i.e., $kT = 46 \pm 10 \text{keV}$) inferred in our spectral analysis.

It is interesting to compare the temporal behavior of XGPS-9 and 2XMMp J131223.4+173659, which is an eclipsing polar serendipitously identified in the 2XMM catalog (Vogel et al. 2008). The properties of these two systems are remarkably similar. First, both objects show a narrow and deep minimum in their phase-folded light curves (i.e., depression in phase 0.97–1.03 for the case of XGPS-9). This feature is interpreted as the eclipse of X-ray emission in the polar region of the white dwarf when the companion star passes through our line of sight toward this region. Also, the broad depression (i.e., phase $\sim 0.2–0.6$ in Figure 3), which is likely due to the self-occultation by the white dwarf itself, is observed in both systems. The coexistence of these two features indicates that the spin of the white dwarf and the binary orbital periods are synchronized. Furthermore, a shallow minimum in the soft-band light curve (in phase $\sim 0.7–0.9$ in Figure 3) is found before the eclipse. When the X-ray emitting region is obscured by the accretion stream, a pre-eclipse dip can be the result of increased photoelectric absorption, which makes the dip more prominent in the soft band (see Figure 3).

We further attempted to place a constraint on the orbital inclination with our estimated eclipse width (i.e., $\sim 320 \text{s}$). Assuming that the companion star fills its Roche lobe and that the X-ray emitting region is close to the surface of the white dwarf, the duration of the total eclipse of the white dwarf can be expressed as a function of the mass ratio and the inclination (cf. Figure 2 in Horne 1985). The eclipse width corresponds to a phase interval of $\Delta \phi \sim 0.06$, which we considered to be an upper limit on the eclipse width, as a longer observation might reveal the falling/rising edges in the eclipse profile. We further assume that the companion star is an M dwarf with mass $M_* \gtrsim 0.1 M_\odot$. For a typical white dwarf (i.e., $M_{wd} \sim 0.6 M_\odot$), this implies a mass ratio of $q = M_* / M_{wd} \gtrsim 0.17$. With these assumptions, the upper bound on the orbital inclination can be placed at $\lesssim 80^\circ$.

For further investigation of XGPS-9, dedicated optical/infrared observations will be useful for confirming its source nature. A differential photometric study can enable a comparison with the X-ray light curve reported in this paper. This can provide information for further constraining the accretion geometry. Also, the free electrons in the shock region can spiral in the magnetized ionized gas. This can lead to the emission of cyclotron radiation in the infrared regime. Therefore, infrared spectroscopy and polarimetry are encouraged for directly determining the magnetic field of the white dwarf. We would also like to point out that the current data cannot provide a conclusive constraint on the plasma temperature of a thermal bremsstrahlung spectrum at a few tens of keV, which is far above the energy coverage of XMM-Newton. This is reflected by the large relative uncertainty reported in this work (i.e., $\gtrsim 20\%$). To better constrain spectral results, hard X-ray observation is certainly needed. As XGPS-9 resides in rather complex region, the recently commenced mission NuSTAR and the upcoming one (e.g., Astro-H), which are equipped with hard X-ray focusing optics, will provide the desirable instruments for further investigations of this interesting eclipsing polar.
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