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AN ACCURATE DETERMINATION OF THE OPTICAL PERIODIC MODULATION IN THE X-RAY BINARY SAX J1808.4−3658

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ABSTRACT

We report on optical imaging of the X-ray binary SAX J1808.4−3658 with the 8-m Gemini South Telescope. The binary, containing an accretion-powered millisecond pulsar, appears to have a large periodic modulation in its quiescent optical emission. In order to clarify the origin of this modulation, we obtained three time-resolved r'-band light curves (LCs) of the source in five days. The LCs can be described by a sinusoid, and the long time-span between them allows us to determine optical period $P = 7251.9$ s and phase 0.671 at MJD 54599.0 (TDB; phase 0.0 corresponds to the ascending node of the pulsar orbit), with uncertainties of 2.8 s and 0.008 (90% confidence), respectively. This periodicity is highly consistent with the X-ray orbital ephemeris. By considering this consistency and the sinusoidal shape of the LCs, we rule out the possibility of the modulation arising from the accretion disk. Our study supports the previous suggestion that the X-ray pulsar becomes rotationally powered in quiescence, with its energy output irradiating the companion star, causing the optical modulation. While it has also been suggested that the accretion disk would be evaporated by the pulsar, we argue that the disk exists and gives rise to the persistent optical emission. The existence of the disk can be verified by long-term, multi-wavelength optical monitoring of the source in quiescence, as an increasing flux and spectral changes from the source would be expected based on the standard disk instability model.

Subject headings: binaries: close — stars: individual (SAX J1808.4−3658) — X-rays: binary — stars: low-mass — stars: neutron

1. INTRODUCTION

While it had long been believed that neutron star (NS) X-ray binaries (XRBs) are progenitors of the recycled millisecond radio pulsars (Bhattacharya & van den Heuvel 1991), it was the discovery of coherent pulsations from the transient XRB SAX J1808.4−3658 (hereafter J1808.4) during its X-ray outburst in 1998 that first and finally confirmed the connection between the two systems (Wijnands & van der Klis 1998): in this binary, the accreting NS is a 2.49 ms X-ray pulsar. As the first example of accretion-powered millisecond pulsar systems, J1808.4 has been extensively studied, with various interesting properties revealed (see Hartman et al. 2008 and references therein). In this paper, we focus on the optical periodic modulation seen in this binary and report on our observational study of the modulation.

The orbital period of J1808.4 is $P_{\rm orb} \simeq 7249.157$ s ($\simeq 2.01$ hr), accurately known to one part in 10^{10} from Doppler modulations of the millisecond pulsations (Chakrabarty & Morgan 1998; Hartman et al. 2008). Combined with the derived mass function of $3.8 \times 10^{-5} M_\odot$, the period implies that the mass-transferring companion could be a 0.17 $M_\odot$ low-mass main-sequence star, but more likely a ∼0.05 $M_\odot$ brown dwarf (Bildsten & Chakrabarty 2001). At a distance of $D = 3.5$ kpc (Galloway & Cumming 2006), the optical

counterpart in quiescence is several magnitudes brighter ($V = 20.7$, $L_V \simeq 3.0 \times 10^{32}$ ergs s^{-1} assuming isotropic emission and extrinction $A_V = 0.73$; see § 2 and § 4) than the possible types of stars suggested as the companion, probably indicating that the optical emission arises from the accretion disk in the binary (Homer et al. 2001). However in the quiescent state, 10–40% sinusoidal-like modulations in the source's optical light curves (LCs) have been reported (Homer et al. 2001; Campana et al. 2004), and this is puzzling because the quiescent X-ray luminosity is approximately $L_{\rm X} \simeq 5 \times 10^{31}$ ergs s^{-1} (e.g., Heinke et al. 2007), two orders of magnitude lower than that required to account for the modulation (Burderi et al. 2003). Typically in a low-mass X-ray binary (LMXB), sinusoidal optical modulation arises from X-ray heating of the companion star by the central X-ray source: the visible area of the heated face varies as a function of orbital phase (e.g., Arons & King 1993). In J1808.4, depending on the companion's star types, only 0.5–1.4% [estimated by $(R_2/D_b)^2/4$, where R_2 is radius of the companion and D_b is the separation distance between the NS and companion] of the total energy flux from the central NS would be received by the companion for isotropic emission. This leads to the suggestion that in quiescence, the NS might switch to be a rotation-powered pulsar so that the rotational energy would be the energy source that heats half surface of the companion star and causes the modulation (Burderi et al. 2003).

However, there are other possibilities that do not require a rotation-powered pulsar, and we have considered whether or not the accretion disk could give rise to the modulation. It has been known that "superhumps", which are commonly seen in short-period cataclysmic variables (CV; Warner 1995), also appear in LMXBs

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(e.g., Haswell et al. 2001). These periodic modulations have periods a few percent longer than the orbital periods and can be sinusoidal-like with an amplitude of ~10%, arising from a precessing, eccentric accretion disk (e.g., Whitehurst & King 1991). Indeed, it has been suggested that those NS LMXBs with $P_{orb} < 4.2$ hr are potential superhump sources (Haswell et al. 2001). In addition, several parts of an accretion disk could contribute significantly to optical modulation (e.g., Mason & Cordova 1982). It has also been suggested that for an X-ray transient, its quiescent optical emission may come from a bright spot on the accretion disk (Menou & McClintock 2001).

In particular, the superhump possibility was suggested by the X-ray LC obtained in the source's 2002 outburst. As shown in Figure 1, the LC exhibits a ~5-day periodic modulation at the end of the outburst. If this indicates the precession periodicity ($P_{prec} \simeq 5$ days) of the accretion disk, it would imply a superhump period of $P_{sh} = 7373$ s ($1/P_{sh} = 1/P_{orb} - 1/P_{prec}$) and superhump excess $\epsilon = 0.017$ [$\epsilon = (P_{sh} - P_{orb})/P_{orb}$] (Patterson 2001). The excess value is consistent with those obtained for cataclysmic variables and LMXBs (Patterson et al. 2005; Haswell et al. 2001). Furthermore, a mass ratio of $q \simeq 0.08$ could be estimated from the relation $\epsilon = 0.18q + 0.29q^2$ (Patterson et al. 2005), implying a companion mass of 0.11 $M_\odot$ for 1.4 $M_\odot$ NS mass. This companion mass is within the range implied by the mass function.

Previously, time-resolved imaging observations over a small period of time (covering only ~1.5 orbital period of the binary) were made. However, these observations were carried out either with a small telescope (Homer et al. 2001) or under very poor observing conditions (Campana et al. 2004), resulting in large uncertainties in the obtained LCs. In order to study the optical emission from J1808.4, and particularly to probe whether it could be a superhump source, we have obtained high quality optical LCs of the source in its quiescent state through time-resolved photometry. The observations were made with the 8-m Gemini South Telescope over five days, allowing us to determine the period and phase of the optical modulation accurately. We note that Heinke et al. (2008) (see also Deloye et al. 2008) recently observed the source simultaneously at X-rays and optical $g'i'$ wavelengths, and from the observations they confirmed the inconsistency between the large amplitude optical modulation and low X-ray luminosity.

2. OBSERVATIONS AND DATA REDUCTION

To determine the periodicity in the source's optical emission accurately, three Gemini queue mode observations of J1808.4 were carried out in five days, on 2008 May 11, 12, and 15. The starting time of each observation was approximately 06 hour (UTC) each day, resulting in a time span of $\simeq 4$ days between the first and third observations. We proposed such observations because we estimated that the time span would allow us to determine the period to <10 s accuracy, and the second observation would be needed to keep the track of the optical periodicity phase. A Sloan r' filter, with the central wavelength at 6300 Å, was used for imaging. The detector was the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004), which consists of three 2048×4608 EEV CCDs.
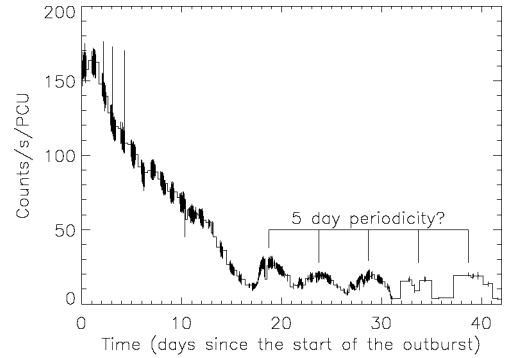

FIG. 1.— X-ray light curve of J1808.4 during its 2002 outburst, obtained with the Proportional Counter Array (PCA; 2–60 keV energy range) on board the *Rossi X-ray Timing Explorer* satellite. Gaps in the light curve were due to Earth occultations of the source. At the end of the outburst, a ~5 day periodicity is tentatively suggested.

We used 2×2 binning, providing a pixel scale is 0.146″ pixel^{-1}. In each night, 36 images of the source were obtained contiguously, each with approximately 3.9 min exposure time. The detector's slow read mode, having 55 s readout time, was used. As a result, the total observation time in each night was approximately 3 hrs, covering 1.5 orbital cycles of J1808.4. The average seeing [full-width half-maximum (FWHM) of the point spread function (PSF) of the images] for the three nights were 0.63″, 0.58″, and 0.70″, respectively. The second night had the best observing conditions, with the seeing reaching 0.51″ a few times during the observation.

We used the Gemini IRAF package GMOS for data reduction. The images were bias subtracted and flat fielded. The bias and flat frames were from GMOS baseline calibrations, made on 2008 May 13 and May 11, respectively. The standard star used for flux calibration was PG1047+003A (Smith et al. 2002). The observation of this star was made on 2008 May 13, also as part of the GMOS baseline calibrations. The airmass of the observation was 1.234, which can be estimated to have caused a zero-magnitude offset of 0.03 mag[4]. We did not add this offset to our brightness measurements given below; instead we consider it as an uncertainty for absolute flux calibration.

We performed PSF-fitting photometry to measure the brightnesses of the source and other in-field stars. A photometry program DOPHOT (Schechter et al. 1993) was used. A finding chart of the target is shown in Figure 2. As can be seen, our target is located between two stars with similar brightnesses. Its distance to star a is 0.6″ and to star b is 1.0″. In a few of images, we have FWHM around 0.8″; in these cases, our target and star a are nearly unseparated. For these images, we positionally calibrated them to a reference image that was combined from four best-quality images in night 2. We determined the positions of our target and star a in the reference image and fixed them at the positions for photometry of the images.

We performed differential photometry to eliminate systematic flux variations in the images. An ensemble of 8 isolated, nonvariable stars in the field were used. The
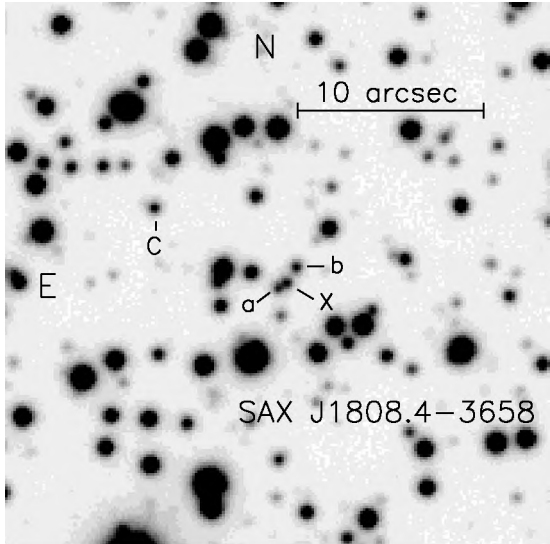
FIG. 2.— Gemini South r' image of the J1808.4 field. Object X, located between star a and b, is the optical counterpart to J1808.4. The star labeled as C is used as a check star.

brightnesses of our target and other stars in each image were calculated relative to the total counts of these stars. Star C (Figure 2) was used as a check star, because it was non-variable and had similar brightness to our target.

We used the third image from the second night to obtain absolute magnitudes of the target and nearby stars, as it is one of the best-quality images. The aperture correction was calculated using 15 in-field stars, with an uncertainty of 0.025 mag. The resulting magnitudes of the target are given in Table 1, and the average magnitudes of the nearby stars a and b, and the check star C were $r' = 21.492 \pm 0.048$, 21.133 ± 0.013, and 21.178 ± 0.013 mag, respectively. The LCs of our target and stars a and C are shown in Figure 3. As can be seen, star a was likely a variable, with the magnitudes and standard deviations of its three LCs being 21.545 ± 0.029, 21.444 ± 0.020, and 21.486 ± 0.021. The difference between the first and second nights is 2.9σ significant. These results are summarized in Table 2.

As we compared our results with those previously reported, we noted that the source magnitudes, resulting from imaging observations made on 1999 July 11 with the Very Large Telescope (VLT) at the European Southern Observatory, are approximately 1 mag lower than the values given by Campana et al. (2004), who analyzed the same data. The data consist of 1 min exposures in the V, R, and I-bands, taken with the high resolution collimator, providing a pixel scale of $0.1''$ pixel^{-1}. The instrumental magnitudes were calibrated against photometric standard stars in the SA110 field (Landolt 1992). We obtained $V = 20.73 \pm 0.04$, $R = 20.59 \pm 0.04$, and $I = 20.15 \pm 0.06$, where the uncertainty is the quadratic sum of the uncertainty in the zeropoint, the aperture correction, and the instrumental magnitude. Comparing the magnitudes of the in-field stars, including star a and b, from the VLT observations and ours, we believe that our magnitude values are correct.

3. PERIODICITY DETERMINATION

As can be seen in Figure 3, the LCs of J1808.4 clearly show a sinusoidal modulation, and appear to

have different average brightnesses, indicating overall variations from day to day. The times of the data points are barycentric corrected, with the JPL Solar System Ephemeris DE405 used. In order to determine the modulation, we fit the LCs with function $m = m_c + m_h \sin[2\pi(t/P + \phi_0)]$, where t is the time, P, ϕ_0, and m_h are the period, starting phase, and semiamplitude of the sinusoidal modulation, respectively. The parameters m_c and m_h were kept as a constant for each LC, but were allowed to have different values in different LCs. As a result, we found that the best-fit sinusoid ($\chi^2 = 1879$ for 100 degrees of freedom) has $P = 7251.9$ s and $\phi_0 = 0.671$ at MJD 54599.0 (TDB; Phase $\phi = 0.0$ corresponds to the ascending node of the pulsar orbit).

While the LCs can be described by the sinusoidal function, as shown in Figure 3, the large χ^2 value indicates large scattering of the data points from the best-fit function. There is a systematic uncertainty caused by our target's proximity to star a. This can be seen from the fact that the standard deviations of the three LCs of star a are significantly larger than its uncertainties from PSF-fitting (the average is 0.013 mag) and the standard deviation (0.013 mag) of all data points of the check star C. In addition, we also independently used the program DAOPHOT in the ESO-MIDAS system for photometry. The resulting LCs are very similar to those resulting from DOPHOT, but with the standard deviations of the differences between the two sets of the LCs being 0.027, 0.019, and 0.014 mag for the three nights. These values are approximately consistent with the standard deviation values of star a, confirming the contamination of the photometry caused by the proximity of our target and star a. Adding the standard deviations of star a in quadrature with the uncertainties of data points (resulting from PSF-fitting) of the target, the χ^2 value is reduced to 266 for 100 degrees of freedom. This indicates that there is intrinsic scattering of the data points from the single sinusoid. For example, we note that the brightest data point in each LC appears at phase 0.05–0.17 after the maximum of the sinusoid. This pattern is likely to be true, because the DOPHOT and DAOPHOT measurements at the LCs' region are nearly identical.

The uncertainty on P is 2.8 s (90% confidence), found from Monte Carlo simulations. We generated 10,000 sets of simulated LCs, each like the sets of the actual data points. In doing that, we used the best-fit parameters and added to each set of LCs Gaussian-distributed deviates, where the Gaussian distribution was estimated from the residuals to the best-fit model. Having standard deviation $\sigma = 0.04$ mag, the Gaussian mimics the relatively large scattering of the data points from the best-fit model. We then fit each set of simulated LCs with a sinusoidal function. The uncertainty on P was determined by the spread of values. We also determined the uncertainty on the phase this way, and found it to be 0.008 (90% confidence). Comparing to the X-ray ephemeris (phase at MJD 54599.0 is $\simeq 0.6714$ with a negligible uncertainty; Hartman et al. 2008), the optical periodicity is consistent with being orbital. We investigated whether the period uncertainty might be caused by the uncertainty on the GMOS exposure recording, because it is not clear how accurate the latter was. We made simulations by assigning randomly produced, uniformly distributed time offsets to the recorded image times, and

found that the period value is not sensitive to any possible offsets. For example, conservatively assuming 1-s uniformly distributed offsets for the GMOS time recording, the resulting period difference has a range of 0.03 s, negligible compared to the statistical period uncertainty.

The average brightness of J1808.4 in the three nights increased from 21.123, to 21.105, to 21.023 mag, while the semiamplitude of the modulation decreased from 0.214, to 0.202, to 0.191 mag (Table 2). These variations may suggest that the two components of the emission, the persistent and modulated, were independent of each other; as the former was increasing, the modulation fraction was decreasing. However the uncertainties on these parameters are relatively large, $\sim$0.04 mag (90% confidence), showing that the variations of the semiamplitude are not significant. This is because each of our observations covered only 1.5 orbital cycles, insufficient for an accurate determination. Therefore we conclude that we have detected an approximately 20% flux modulation from J1808.4 in r' band. In addition, the optical peaks correspond to when the pulsar is right in front of the companion (superior conjunction of the companion; 270° mean orbital longitude), confirming the previous results from Homer et al. (2001) and Campana et al. (2004).

4. DISCUSSION

Using the 8-m Gemini South Telescope, we have obtained, for the first time, well-determined LCs from J1808.4 in its quiescent state over a time span of four days. From the above studies of the LCs, we find that the optical period and phase are consistent with the X-ray ephemeris, indicating that the optical modulation is orbital in origin. In studies of several tens of LMXBs at optical wavelengths (e.g., van Paradijs & McClintock 1995), in no instance has there been an accretion disk giving rise to a sinusoidal modulation at the orbital period. In addition, the sinusoidal maximum must correspond to superior conjunction of the companion star. Because of these, we rule out the possible disk origin for the modulation that we have suspected. However, the source in outburst could still be a superhumper, which might have been hinted in the X-ray LC (Figure 1). As the outward extension of accretion disks in outburst has both been observed and reproduced in disk instability simulations (Osaki 1996; Dubus et al. 2001), it would not be unexpected for the accretion disk in J1808.4 to have extended to the resonance zone during the 2002 outburst, developing into an eccentric form due to the tidal instability (Whitehurst & King 1991). In fact, superhumps have been seen in outbursts of both black-hole and NS LMXB systems (O'Donoghue & Charles 1996; Elebert et al. 2008). In order to determine this possibility for the long periodicity seen in the 2002 outburst, time-resolved imaging observations, like ours, of the source in outburst are needed. Since the source will be as bright as $\sim$17 mag in an outburst (e.g., Giles et al. 1999; Wang et al. 2001), a search for superhump modulation will be feasible even with a small telescope.

Based on the current observational studies of LMXBs (e.g., van Paradijs & McClintock 1995), it seems extremely unlikely that the observed optical modulation would arise from a source other than the companion star. Thus far, pulsar wind heating of the companion is the only model that has been suggested (Burderi et al. 2003; Campana et al. 2004). The long term spin-down rate of the pulsar has been measured, indicating a rotational energy loss rate of 9×10^{33} ergs s^{-1} (Hartman et al. 2008). This energy output, presumably in the form of a pulsar wind, would illuminate the companion star. Assuming isotropic emission and a brown dwarf companion (Bildsten & Chakrabarty 2001), the fraction of the total energy received by the companion is $\sim$0.005$\eta_*(R_2/0.13\ R_\odot)^2$, where η_* is the fraction of the received energy absorbed by the companion. Following Arons & King (1993), the companion's heated face would have temperature $\sim$7430$\eta_*^{1/4}$ K, due to pulsar wind heating by the putative rotation-powered pulsar. Using such a hot face that varies following a function of $[1 + \sin i \sin(2\pi t/P)]$, where i is the inclination angle of the binary, and also including a constant flux component F_C, we tested whether we could re-generate the averaged LCs of J1808.4. The distance and extinction to the source were fixed at 3.5 kpc and $A_V = 0.73$, respectively, where the extinction value is estimated from $A_V = N_H/0.179 \times 10^{22}$ cm^{-2} by assuming hydrogen column density to the source $N_H = 0.13\times10^{22}$ cm^{-2} (Dickey & Lockman 1990; Heinke et al. 2007). The extinction law for Sloan filters given by Schlegel et al. (1998) was used. We found that the parameter values of $i \simeq 63°$ ($M_2 \simeq 0.049 M_\odot$), $\eta_* \simeq 0.46$, and $F_C \simeq 19\ \mu$Jy can provide the observed modulation (the resulting $\chi^2 \simeq 2100$, with no systematic uncertainties considered). Although we used a very simple model, these derived parameter values are consistent with its known properties. In addition to the fact that the companion is likely a $\sim$0.05 $M_\odot$ star, the source shows no X-ray eclipses or dips, implying $i \leq 70°$. The obtained η_* values are within the range found for two binary radio pulsars (Stappers et al. 2001; Reynolds et al. 2007), in which it is known that the companion is irradiated by the pulsar wind. Therefore, it is plausible that the NS in J1808.4 does turn into a rotation-powered pulsar in quiescence, giving rise to the optical modulation. We note that very recently, Deloye et al. (2008) used an advanced model to fit their $g'i'$ light curves, and also found that the required heating energy should be $\sim 10^{34}$ ergs s^{-1}, consistent with the derived spin-down luminosity (which has 30% uncertainty; Hartman et al. 2008).

The origin of the persistent optical emission is not clear. Homer et al. (2001) tried explaining the emission from an X-ray irradiated disk around the pulsar, but it may not be appropriate to use a steady thin disk model to describe a disk in the thermally stable cold state (lower cold branch of the standard thermal equilibrium S-curve; e.g., Lasota 2001), since a disk temperature profile in the cold state can be drastically different from the hot state (the steady disk case). Campana et al. (2004) used a shock front, arising from the interaction between the companion star and pulsar wind, and the irradiated companion to account for the emission. Here we argue that the accretion disk in quiescence exists, against the suggestion that the disk would be evaporated by the pulsar (Burderi et al. 2003; Heinke et al. 2008), and this can be tested by monitoring J1808.4 at optical wavelengths.

According to the standard disk instability model (DIM; e.g., Osaki 1996; Lasota 2001), while the mass accre-
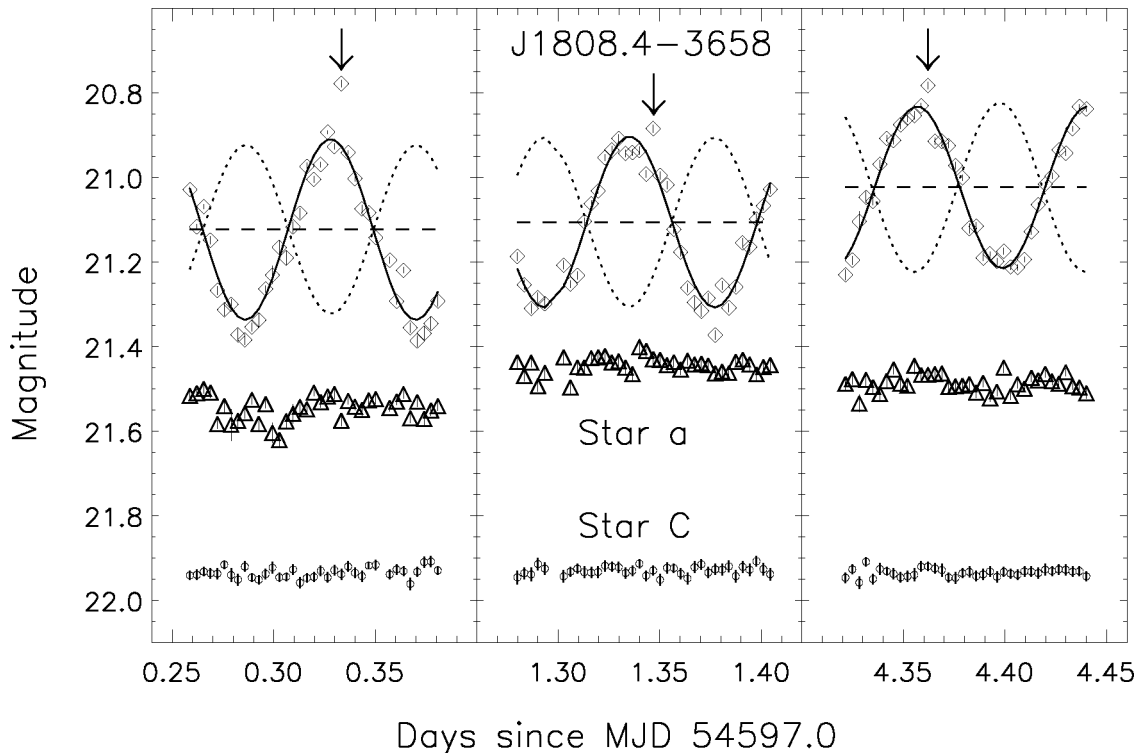
FIG. 3.— Optical r' light curves of J1808.4 (diamonds), in which sinusoidal modulation is clearly visible. For comparison, the LCs of the nearby star a (triangles) and check star C (circles, downward shifted by 0.8 mag) are also shown. The best-fit sinusoidal function to the LCs of J1808.4 is shown as the solid curves, while the constant magnitude for each LC is indicated by the dashed lines. The optical periodicity well matches the X-ray ephemeris (dotted curves), which gives the mean orbital longitude of the binary (Hartman et al. 2008). The optical brightness peaks correspond to when the pulsar is right in front of the companion star (270° mean orbital longitude). The brightest data points in the LCs, indicated by arrows, are at phase 0.05-0.17 after the maxima of the sinusoid.

tion rate to the NS in J1808.4 is very low during quiescence, $\dot{M}_{\rm acc} \leq 6.2 \times 10^{-15}$ $M_\odot$ yr^{-1} (estimated from the observed X-ray flux), the average mass transfer rate from the companion to the accretion disk is as high as $\sim 10^{-11} M_\odot$ yr^{-1} (estimated from the X-ray fluence in each outburst; Galloway 2008). The transferred mass is stored in the disk, building up the surface density for triggering the next outburst. The average persistent r' flux from J1808.4 in our observations is estimated to be $F_C = 19$ μJy, corresponding to a disk luminosity of $L_{r'} = 2\pi D^2 F_C / \cos i \simeq 1.5 \times 10^{32}$ ergs s^{-1} ($i = 63°$ is assumed). There is plenty of gravitational energy available to power this emission as matter moves inwards through the outer disk. At the time average accretion rate of $\dot{M} \sim 10^{-11}$ $M_\odot$ yr^{-1}, matter falling into a radius of 4000 km releases gravitational energy at a rate that matches the observed luminosity. This radius is far larger than those that are suggested for the inner radius $r_{\rm in}$ of the disk. Generally, $r_{\rm in}$ would be close to the Alfvén radius, $r_{\rm in} \simeq 56$ km $(\dot{M}_{\rm in}/10^{-11} M_\odot {\rm yr}^{-1})^{-2/7} (\mu/10^{26} {\rm~G~cm}^3)^{4/7}$, where $\dot{M}_{\rm in}$ is the mass accretion rate in the inner edge of the disk and μ is the magnetic moment, $\mu \simeq 10^{26}$ G cm^3 for J1808.4 (Hartman et al. 2008). In the cold state, $\dot{M}_{\rm in}$ would be lower than $\dot{M}$, and we note that for $\dot{M}_{\rm in} = 0.1\dot{M}$ (Dubus et al. 2001), $r_{\rm in}$ is 110 km. However, since a radio pulsar presumably would have no interactions with a surrounding disk, $r_{\rm in}$ would be larger than the light cylinder radius of the pulsar, which is 120 km. As can be seen, it is possible that in quiescence, the disk in J1808.4

would be outside of the light cyliner. In addition, the disk temperature profile in quiescence may be described by a constant, at least right after an outburst (e.g., Osaki 1996; Dubus et al. 2001). For J1808.4, we find that an effective temperature of 4600 K for the disk can give rise to the persistent r' flux, where the disk is assumed to be cut off at the tidal radius 3.7×10^{10} cm ($\simeq 0.9 R_1$, where R_1 is the NS's Roche lobe radius). This temperature value is consistent with those typically considered in the DIM (Lasota 2001; the critical effective temperature for having an outburst is ~ 6000 K).

In order to verify our suggestion that the persistent optical emission arises from the disk, long-term, multiwavelength optical monitoring of the source in its quiescent period is required. From such observations, we might expect to see an increasing flux from the source. Moreover, since in the DIM the temperature profile as a function of disk radius is predicted to be changing, turning from a constant right after an outburst to a power-law–like function prior to the next outburst (e.g., Dubus et al. 2001), we would also see flux spectrum changes. This type of well-behaved changes would not be expected from the pulsar wind shock model (Campana et al. 2004), thus allowing to determine the origin of the persistent emission.

If the companion star is irradiated by the pulsar wind, there is no reason to think that the disk is not. It has been suggested that the disk in quiescence might be evaporated by the pulsar (e.g., Burderi et al. 2003; Heinke et al. 2008), but according to the recent calculations by Jones (2007), a pulsar wind may only be effective

in heating a disk. Basically, as X-rays from a NS would ionize the surface of a disk, the Poynting flux, which is dominant in a wind when it is not far from the light cylinder of the pulsar, would interact with the ionized particles, converting energy into disk heating. Using equation (16) in Jones (2007), we estimate that the baryon loss rate of the disk at the inner radius is approximately $3\times10^{21}(r_{in}/120$ km$)^{-3}$ cm^{-2} s^{-1}, only 0.05% of the surface density ($\sim$10–100 g cm^{-2}) that is generally considered in the accretion disk models (e.g., Dubus et al. 2001). This suggests that the disk in J1808.4 could exist and might be irradiated by the pulsar wind. However, using the model provided by Jones (2008), the flux due to pulsar wind heating would be 2 μJy for parameter $\zeta = 0.3$ ($0.03 \lesssim \zeta \lesssim 0.3$ and a larger ζ value corresponds to a higher disk effective temperature; see details in Jones 2008). The flux would be 10% of the average r' flux, which would suggest a weak pulsar-wind heating effect in J1808.4.

Finally, it will be of great interest if J1808.4 can be determined to become rotation-powered during quiescence. We note that the source could be very similar to PSR J2051$-$0827 (Stappers et al. 1996), a binary millisecond pulsar system. For example, the latter has an orbital period of 2.38 hr and a mass function of 1.0×10^{-5} $M_\odot$, and the pulsar has a spin-down luminosity of 6×10^{33} ergs s^{-1}. However, searches for pulsed radio emission from J1808.4 have not been successful (e.g., Burgay et al.

2003). Here we suggest that the source might be identified by searching for its pulsed γ-ray emission. Observations of millisecond pulsars suggest that their efficiency at γ-ray energies may be as high as $\sim$7% (Kuiper et al. 2000). This implies a γ-ray flux of $\sim5\times10^{-13}$ ergs cm^{-2} s^{-1} for J1808.4, possibly detectable by deep observations with *Fermi Gamma-Ray Space Telescope*.

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TABLE 1
PHOTOMETRY OF J1808.4

MJD[a]	r'	$\Delta r'$ [b]
0.257907	21.028	0.006
0.261323	21.116	0.006
0.264715	21.069	0.006
0.268084	21.148	0.009
0.271469	21.267	0.010

NOTE. — Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
[a] Days since MJD 54597.0. [b] 1σ uncertainty resulting from PSF fitting.

TABLE 2
SUMMARY OF BRIGHTNESSES OF NEARBY STARS AND J1808.4
IN OUR OBSERVATIONS

Source	Obs 1 (MJD 54597)	Obs 2 (MJD 54598)	Obs 3 (MJD 54601)
Star a	21.545 ± 0.029	21.444 ± 0.020	21.486 ± 0.021
Star b[a]		21.133 ± 0.013	
Star C[a]		21.178 ± 0.013	
Sinusoidal fitting			
J1808.4			
Average magnitude[b]	21.12	21.11	21.02
Semiamplitude[b]	0.21	0.20	0.19

NOTE. — Uncertainties of 0.025 mag and probable 0.03 mag from the aperture correction and zero point calibration, respectively, are not included.
[a] Average magnitude is derived from all three observations. [b] Uncertainties (90% confidence) are $\sim$0.04 mag.