Time-Resolved Photometry of the Optical Counterpart of Swift J2319.4+2619

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ABSTRACT. Time-resolved CCD photometry is presented of the V ~ 17 optical counterpart of the newly discovered hard-X-ray–emitting polar Swift J2619.4+2619. A total of ~20 hr of data obtained over five nights in various bandpasses (B, V, R, and I) reveals a strong quasi-sinusoidal modulation in the light curve at a best-fitting period of 0.1254 days (3.01 hr), which we associate with the orbital period of the system (one-day aliases of this period at 0.1114 days and 0.1435 days are considered, but appear to be ruled out by our analysis). The amplitude of the modulation increases with wavelength from ~0.8 mag in B to ~1.1 mag in R and I. The increase in amplitude with wavelength is typical of polar systems where the modulated radiation comes from cyclotron emission. The combination of the relatively long orbital period and the emission of hard X-rays suggest that Swift J2619.4+2619 may be a good candidate for an asynchronous polar system.

1. INTRODUCTION

The magnetic cataclysmic variables (mCVs) form a subclass of the cataclysmic variables stars consisting of a low-mass late-type dwarf that fills its Roche lobe and transfers mass to a magnetic white dwarf companion (e.g., see Warner 1995; Wickramasinghe & Ferrario 2000). In the most highly magnetic systems, the polars (a.k.a. AM Her stars), the white dwarf’s magnetic field is sufficiently strong to lock it into synchronous rotation with the orbit and to inhibit the formation of an accretion disk, forcing the transferred gas to accrete onto one (or sometimes both) of the white dwarf’s magnetic poles. In the intermediate polars (IPs; a.k.a. DQ Her stars), the magnetic field strength is insufficient to phase lock the white dwarf, and accretion occurs onto both magnetic poles via a truncated accretion disk. In recent years, a third type of mCV has been recognized, the asynchronous polars, where the white dwarf rotates slightly (~1%–2%) out of synchronism with the orbit (Campbell & Schwore 1999). In all mCVs, a high-temperature (T ≥ 10⁸ K) shock is formed at the base of the accretion column, resulting in the emission of X-rays through bremsstrahlung radiation. At the relatively high magnetic field strengths typical of polar systems (B ≥ 10 MG), a significant component of the cooling in the postshock gas also occurs via polarized optical and infrared cyclotron radiation, which tends to lower the temperature of the postshock gas and soften the X-ray spectrum (Lamb & Masters 1979). Because the cyclotron radiation is beamed preferentially in directions perpendicular to the field lines, the changing aspect of the accretion column results in a significant modulation in the optical and infrared light curves at the orbital period of the binary.

A series of X-ray and optical spectroscopic observations reported in Mukai et al. (2007) have shown that the recently identified Swift/BAT source, Swift J2319.4+2619, is likely to be a rare hard-X-ray–emitting polar. The object was detected initially as a Swift/BAT source with a 15–100 keV spectrum that could be fitted with either a power law of photon index 2.7, or a bremsstrahlung spectrum (kT = 19 keV), with a 15–50 keV flux of 1.05 × 10⁻¹¹ ergs cm⁻² s⁻¹. Later, pointed Swift/XRT observations obtained in 2007 May and June enabled Mukai et al. to identify Swift J2319.4+2619 both with the ROSAT All-sky Survey source 1RXS J231930.9+261525, and with a probable optical counterpart, USNO B1 1162-0585089. Follow-up spectroscopic observations then revealed strong Balmer and He II emission lines typical of polars. In this paper we present time-resolved multicolor CCD photometry of the optical counterpart of Swift J2319.4+2619, first reported in Shafter et al. (2007), which has enabled us to determine the likely orbital period of the system. We conclude by discussing the possibility that future observations may reveal Swift J2319.4+2619 to be a member of the class of asynchronous polars.

2. OBSERVATIONS

A finding chart for the optical counterpart to Swift J2319.4+2619 is shown in Figure 1, with the coordinates taken from Mukai et al. (2007). Observations were carried out during five nights in 2007 December using the Mount Laguna Observatory 1-m reflector. Each night, a series of one-minute exposures were taken through either a Johnson-Cousins B, V, R, or I filter (see Bessel 1990), and imaged on a Loral 2048² CCD. To decrease the readout time between exposures, only a 600 × 600 subsec- tion of the full array was read out. The subsection was chosen to include Swift J2319.4+2619 and several relatively bright nearby field stars to be used for differential photometry. A summary of observations is presented in Table 1.

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The data were processed in a standard fashion (bias subtraction and flat-fielding) using IRAF. The individual images were subsequently aligned to a common coordinate system and instrumental magnitudes for Swift J2319.4+2619 and a nearby comparison star were then determined using the IRAF APPHOT package. Variations in atmospheric transparency were removed to first order by dividing the flux of Swift J2319.4+2619 by that of a nearby comparison star located approximately 2.5' W and 1' S of the variable (star "C" in Fig. 1). The differential light curves were then placed on an absolute scale by calibrating the comparison star against standard stars from Landolt (1992). For the comparison star, C, we find $V = 13.26 \pm 0.10$, $B - V = 0.98 \pm 0.10$, $V - R = 0.49 \pm 0.10$, and $V - I = 1.06 \pm 0.10$. The final calibrated light curves of Swift J2319.4+2619 are displayed in Figure 2.

3. THE ORBITAL PERIOD

In polar systems a significant component of the optical radiation comes from cyclotron emission radiated from the accretion column. Because the white dwarf’s rotation (and, hence, its magnetic axis) is locked into synchronism with the orbit, polar systems show strong modulations in their optical radiation at the orbital period of the binary. The nature of the modulation depends largely on the system geometry; specifically, the orientation of the magnetic axis relative to the spin axis, and the orientation of the orbital plane to our line of sight. In cases where the accreting column is visible throughout the orbit, the light curve is quasi-sinusoidal, with the observed modulation

\begin{table}
\centering
\begin{tabular}{cccrr}
\hline
UT Date & UT Time & Time Resolution & Number of Exposures & Filter \\
& (start of observations) & (sec) & & \\
\hline
2007 Dec 03 & 01:55:30.0 & 63.5 & 285 & V \\
2007 Dec 04 & 01:55:30.0 & 63.5 & 285 & B \\
2007 Dec 05 & 01:38:30.0 & 63.5 & 315 & R \\
2007 Dec 14 & 01:45:30.0 & 63.5 & 210 & I \\
2007 Dec 16 & 02:04:30.0 & 63.5 & 203 & R \\
\hline
\end{tabular}
\caption{Summary of Observations}
\end{table}

\begin{itemize}
\item Mean time interval between exposures (integration time plus readout time)
\end{itemize}
arising from the combined effects of cyclotron beaming and the changing orientation of the magnetic field axis to our line of sight. Alternatively, if the accreting magnetic pole passes behind the limb of the white dwarf during part of the orbit, the light curve will be characterized by flat intervals (during self-eclipse of the accretion column) followed by broad “humps” when the column is visible. The former systems are often referred to as “one-pole” systems because the accreting pole is the only pole ever visible, with the latter systems, which have the nonaccreting pole visible during the part of the orbit when the accreting pole is hidden, referred to as “two-pole” systems (Cropper 1990).

The photometry of Swift J2319.4+2619 shown in Figure 2 clearly reveals a quasi-sinusoidal modulation with a timescale of \( \sim 3 \) hr, indicating that the object is a one-pole system. As expected for cyclotron emission in polars, the amplitude of the modulation increases with wavelength, in this case with values ranging from 0.8 mag in \( B \) to 1.1 mag in \( R \) and \( I \). We determined the period of the modulation using two approaches. Initially, we estimated times of maximum light from the point of intersection of straight line segments fitted by eye to the ascending and descending portions of the hump profiles. During the five nights of observation, we observed a total of eight maxima. The resulting timings, which we estimate to be accurate to \( \pm 5 \) minutes, are given in Table 2. A linear least-squares fit of these timings yields the following ephemeris for the times of maximum light in Swift J2319.4+2619:

\[
T_{\text{max}} = \text{HJD } 2,454,437.618(2) + 0.12544(3)E. \tag{1}
\]

Residuals of the measured timings with respect to equation (1) are also included in Table 2.

Next, to make a more thorough period search, including possible alias periods, we analyzed the entire data set by computing a Scargle (1982) periodogram. Given that the light curves were obtained in different colors with differing amplitudes and zero points, we converted all light curves to relative flux with maxima normalized to unity prior to computing the periodogram. The results of this analysis are shown in Figure 3. The 0.1254 day period determined above is clearly favored; however, it is not obvious that the one cycle per day aliases of this period (0.1114 days and 0.1435 days) can be ruled out definitively.

In order to explore the viability of these alias periods, we have performed two additional exercises. First, we have reproduced in Figure 4 the light curves from the first three nights of observation, where we covered two maxima, showing the times of maxima expected for the best-fitting period and its one-day aliases. We have chosen to anchor the timings to the second maxima in each case because these maxima are the best defined (most symmetrical). Clearly, the shorter alias period \( P = 0.1114 \) days, dotted line) appears to be too short to match the light curves, particularly in the case of the \( R \)-band light curve. On the other hand, the longer alias period \( P = 0.1435 \) days, dashed line) clearly appears to be too long in all cases.

As a final test, we have phased the light curves with each of the three periods, and plotted the normalized and phased light curves in Figure 5. The 0.1254 day period clearly produces the phased light curve with the least scatter, indicating that it provides the best fit to the data. Taken together, the analyses presented above strongly favor the 0.1254 day period, and we adopt this as the likely orbital period of Swift J2319.4+2619.

### 4. DISCUSSION

Swift J2319.4+2619 is somewhat unusual (for a polar) given the strength of its hard X-ray emission. It has long been recognized that among mCVs, polars have relatively soft X-ray spectra compared with the IP systems (Kuijpers & Pringle 1982; Lamb 1985). The ratio of hard-to-soft X-ray emission in a mCV depends strongly on the magnetic moment of the white dwarf. White dwarfs with high magnetic moments (high fields

![Fig. 3.—Periodogram analysis of the complete set of light-curve data. The highest peak corresponds to the favored period of \( P = 0.1254 \) days, and is bracketed by one-day aliases of \( P = 0.1435 \) days and \( P = 0.1114 \) days.](image)

![Table 2](table)

**TABLE 2**

| HJD (peak) (2,450,000+) | Cycle Number (E) | \( O - C \) (×10\(^{-3}\) day) |
|-------------------------|-----------------|------------------|
| 4437.616 \( \ldots \)  | 0               | \(-2.306\)        |
| 4437.739 \( \ldots \)  | 1               | \(-4.748\)        |
| 4438.628 \( \ldots \)  | 8               | \(-6.153\)        |
| 4438.747 \( \ldots \)  | 9               | \(-0.289\)        |
| 4439.264 \( \ldots \)  | 16              | \(-1.387\)        |
| 4439.754 \( \ldots \)  | 17              | \(3.170\)         |
| 4448.658 \( \ldots \)  | 88              | \(0.744\)         |
| 4450.663 \( \ldots \)  | 104             | \(-1.337\)        |

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and low masses) are expected to have strong soft X-ray emission, with low-field high-mass systems expected to radiate significant hard X-ray emission (e.g., see Lamb & Masters 1979; Cropper et al. 1998). The dominant postshock cooling mechanism in high-field systems, such as polars, is cyclotron emission, which tends to decrease the postshock temperature and suppress hard-X-ray emission, as would a lower-mass white dwarf. On the other hand, the higher temperatures required to produce the hard-X-ray emission seen in IPs can be produced in a lower-field system, which would be expected to cool primarily through bremsstrahlung radiation, or in a system with a high-mass white dwarf, or both. In a recent study of cataclysmic variables discovered in the INTEGRAL/IBIS survey, Barlow et al. (2006) found that IP systems (and the asynchronous polar systems) were significantly more likely to be detected in the hard 20–100 keV energy band than were polar systems. In the sample of 19 cataclysmic variables discovered by IBIS, 14 are known or suspected magnetic systems. Of these, V834 Cen is the only polar. Among the rest, 11 are IPs, two are asynchronous polars, and one is a bright (and nearby) dwarf nova (SS Cyg).

The majority (13) of the 19 hard X-ray bright systems have known orbital periods, and all but one, the polar V834 Cen, have periods in excess of the well-known 2–3 hr gap in the orbital period distribution of cataclysmic variables. Although it appears that the gap is less well defined for mCVs, it remains true that the IPs typically have orbital periods above the gap, whereas polar systems are mostly concentrated at orbital periods below the gap (e.g., Webbink & Wickramasinghe 2002). The generally accepted explanation for this segregation is that the smaller binary dimensions and lower mass accretion rates characteristic of the short period systems make it easier for white dwarfs with a given magnetic moment to become locked in synchronism with the orbit (e.g., King et al. 1985). Patterson (1994) has estimated the minimum field strength necessary to phase lock a white dwarf of a given mass, $M_{\text{wd}}$, in a system with orbital period, $P_{\text{orb}}$, as

$$B_7 \gtrsim 1.5 M_{\text{wd}}^{1.1} P_{2.8}^{2.8},$$

(2)
where $B_7$ is the magnetic field strength in units of $10^7 \, G$, $M_{wd}$ is the white dwarf mass in solar units, and $P_2 = P_{orb}/2 \, h$.

The orbital period of Swift J2319.4+2619, as determined from the observed photometric modulation, places the system just above the 2–3 hr period gap. The combination of the relatively long orbital period (for a polar), coupled with the strong hard-X-ray emission, suggests that it may be difficult to phase lock the white dwarf in this system. In particular, as noted earlier the hard-X-ray emission suggests either a low field strength, or high white dwarf mass, or both. However, as can be seen from equation (2), these requirements make synchronism increasingly difficult to achieve at long orbital periods.

4.1. Is Swift J2319.4+2619 an Unrecognized Asynchronous Polar?

Taken together, the observed properties of Swift J2319.4+2619 raise the possibility that the system may be a member of the (rare?) class of asynchronous polars. In such systems, of which there are currently only four known (BY Cam, V1500 Cyg, V1432 Aql, CD Ind), the white dwarf spin period and the orbital period differ by $\sim 1\%–2\%$ (Patterson et al. 1995; Campell & Schwope 1999). The cause of the slight asynchronism in these systems is unknown, but may be caused by recent (recorded or unrecorded) nova eruptions (V1500 Cyg is a known nova, Nova Cyg 1975), or, as suggested by Patterson et al. (1995), by the difficulty in synchronizing white dwarfs at longer orbital periods (among the four known asynchronous polars, all but CD Ind have orbital periods in excess of 3.3 hr). The latter explanation would seem to be relevant to BY Cam and V1432 Aql, where the orbital periods ($\sim 3.36$ hr) and estimated white dwarf masses ($\sim 1 \, M_\odot$; Ramsay 2000) suggest via equation (2) that $B \gtrsim 60 \, M_{\odot}$ would be required to synchronize the white dwarfs in these systems. Although the field strength in V1432 Aql is unknown, in BY Cam it is estimated to be $\sim 41 \, M_{\odot}$ (Cropper et al. 1989), which would appear insufficient to assure synchronism of the white dwarf.

It is possible that asynchronous polar systems may be considerably more common than is implied by the small number of systems currently known. In order to classify a mCV as an asynchronous polar, it is clearly necessary to establish the orbital period independently of any photometric (or polarimetric) modulation tied to the white dwarf rotation. The orbital periods in polars are difficult to measure directly unless the system is eclipsing. For non-eclipsing systems, such as Swift J2319.4+2619, the orbital period can be measured directly only if spectral features from the secondary star are visible, and a radial velocity curve can be determined. Future observations of Swift J2319.4+2619, particularly if the system enters a low state when the relative contribution of the secondary star’s light to the overall system luminosity is increased, should focus on the detection of spectral features from the secondary star. For an orbital period of 3 hr, the secondary star is expected to have a spectral type of $\sim$M4–5 (Smith and Dhillon 1998), and would be most easily detected in the near infrared, for example through the Na I doublet at 8183, 8194 Å.

5. CONCLUSIONS

We have presented five nights of multicolor CCD photometry of the optical counterpart of Swift J2319.4+2619, which has been recently identified as a hard X-ray emitting polar by Mukai et al. (2007). Our principal conclusions are as follows:

1. A strong, quasi-sinusoidal photometric modulation is seen in the light curve with a best-fitting period of 0.1254 days (3.01 hr), which we identify as the likely orbital period of the system. A detailed analysis of the data appears to rule out the one-day aliases of this period at $P = 0.1114$ days (2.67 hr) and $P = 0.1435$ days (3.44 hr) as viable orbital period candidates.

2. The sinusoidal nature of the modulation suggests that Swift J2319.4+2619 is a “one-pole” accretor; however, a determination of the detailed accretion geometry and magnetic field strength will require future time-resolved polarimetric observations.

3. The amplitude of the modulation ranges from $\sim 0.8$ mag in $B$ to $\sim 1.1$ mag in the $R$ and $I$ bands. The slight increase in the amplitude of the modulation with wavelength is characteristic of the cyclotron emission produced at typical polar field strengths, providing additional support for the identification of Swift J2319.4+2619 as a polar system.

4. The relatively long orbital period, coupled with strong hard-X-ray emission observed by Mukai et al. (2007) suggests that Swift J2319.4+2619 may be an asynchronous polar. In order to determine if the white dwarf rotates synchronously with the orbit, future observations should focus on detecting radial velocity variations of the secondary star, which will allow an independent determination of the orbital period of the system.

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