A PARAMETERIZATION STUDY OF THE PROPERTIES OF THE X-RAY DIPS
IN THE LOW-MASS X-RAY BINARY X1916—053

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ABSTRACT

The ultracompact low-mass X-ray binary X1916—053, which is composed of a neutron star and a semidegenerate white dwarf, exhibits periodic X-ray dips of variable width and depth. We have developed a new method to parameterize this dipping behavior to systematically study its variations. This can help in further understanding binary and accretion disk behaviors. Observations by the Rossi X-Ray Timing Explorer from 1998 clearly show a 4.87 day periodic variation in the dip width. This is probably due to nodal precession of the accretion disk, although an epoch-folding search finds no significant sidebands in the spectrum. From the negative-superhump model of Larwood et al., the mass ratio can be estimated as $q = 0.045$. Combining more than 24 years of historical data, we find an orbital period derivative $P_{\text{orb}}/P_{\text{orb}} = (1.62 \pm 0.34) \times 10^{-7}$ yr$^{-1}$ and establish a quadratic ephemeris for the X-ray dips. This period derivative seems inconsistent with the prediction from the standard model of binary orbital evolution proposed by Rappaport et al. On the other hand, Tavani’s radiation-driven model can properly account for the period derivative, although the large mass outflow predicted by this model has never been observed in this system. With the best ephemeris, we find that the standard deviation of the primary dips is smaller than that of the secondary dips. This means that the primary dips are more stable than the secondary dips. Thus, we conclude that the primary dips of X1916—053 occur from the bulge where the accretion stream encounters the rim of the disk, rather than the inner disk ring as previously proposed by Frank et al.

Subject headings: stars: individual (X1916—053) — X-rays: binaries — X-rays: individual (X1916—053)

1. INTRODUCTION

Some X-ray binaries exhibit periodic dips in their X-ray light curves. To date, there are 11 X-ray binaries known for such periodic dipping features (Ritter & Kolb 2003). It is widely believed that these dips are caused by X-rays from the region around the compact object being periodically absorbed by the vertical structure in the outer part of the accretion disk. The periodic dips provide us with an opportunity to measure the orbital period and investigate the accretion disk dynamics of the binary system.

The low-mass X-ray binary X1916—053 (4U 1915 — 05), which is composed of a neutron star and a white dwarf companion, exhibits various timing properties. The binary orbital period can be obtained from periodic intensity dips in its X-ray light curves. Walter et al. (1982) and White & Swank (1982) first discovered these X-ray dips with Einstein and OSO 8 observations. White & Swank found two possible periods of $49.93 \pm 0.06$ and $50.06 \pm 0.03$ minutes, the shortest among all X-ray dippers. Homer et al. (2001) used the $O-C$ (observed minus calculated) technique on the Rossi X-Ray Timing Explorer (RXTE) observational data from 1998 to calculate a best-fitting period of $3000.6 \pm 0.2$ s. Chou et al. (2001) used data from 1997—1996 to derive an orbital period of $3000.6508 \pm 0.0009$ s and established an X-ray dip ephemeris. In addition to the $\sim 3000$ s recurrent dips, secondary dips are also occasionally seen at phases from $\sim 0.4$ to $\sim 0.6$ relative to the center of the primary dips.

The optical modulation period of X1916—053 is $3027.5510 \pm 0.0052$ s, which, although only by $\sim 1\%$, is significantly longer than the X-ray dip period (Chou et al. 2001). Optical observations revealed the $3000$ s X-ray period (Grindlay 1989, 1992), whereas the $3028$ s optical period, which has a series of $\sim 3.9$ day sidebands, was detected in the X-ray light curves (Chou et al. 2001). The optical period was once considered to be the orbital period of the system, with the X-ray dip period being the beat period of the binary orbital period and a third companion with orbital period $\sim 3.9$ days (Grindlay et al. 1988). However, Chou et al. (2001) concluded that the X-ray dip period, as in other dipping sources, is the orbital period. Further, they concluded that the optical modulation is likely caused by the coupling of the orbital motion with a $3.9$ day disk apsidal precession period, like the superhumps in SU Ursae Majoris type dwarf novae. Furthermore, Retter et al. (2002) discovered a negative superhump with a period of $2979.3$ s, which is the beat period between the orbital period and the $\sim 4.8$ day disk nodal precession period.

On the other hand, modulation of the dips’ shape was first found in Ginga data (Yoshida et al. 1995). Because of the shortness of the observation, the modulation period could only be constrained to $\sim 5$—$6$ days. Chou et al. (2001) found that the dip phase probably modulates with a $4.85$ or $3.76$ day period by analyzing 10 consecutive days of RXTE observations from 1996. A dip phase variation with amplitude $\sim 0.05$ and period of $4.74$ days was seen in another 10 days of consecutive RXTE observations in 1998 (Homer et al. 2001).

Dip shape modulation provides an opportunity to study the dynamics of the disk. Unfortunately, the shape of these dips has not been quantitatively investigated before. For example, to investigate possible periods between 3.5 and 5 days, Homer et al. (2001) considered the area, length, and depth of the dips and the phase of deepest dip, but none of these clearly indicate a $\sim 4$ day cycle. In this paper, we develop a new method to parameterize the properties of the X-ray dip to further investigate its variation using archival data from various observatories that span a total of more than 24 years.

In § 2, we briefly introduce the historical data applied in this study and the corresponding basic reductions. Section 3 describes the data analysis method, including the definitions of the dip center,
width, and strength, as well as the results, such as the periodic variation in dip width, the long-term orbital ephemeris, and the stability of primary and secondary dips. Finally, we discuss interpretations from our analysis of the nodal precession of the accretion disk and the period derivative of the system in § 4.

2. OBSERVATIONS AND DATA REDUCTION

Many X-ray observatories have observed X1916–053 since its discovery. More than 24 years of observational data, from OSO 8 (1978) to XMM-Newton (2002), have been reduced with standard procedures and archived on the HEASARC (NASA’s High Energy Astrophysics Science Archive Research Center) Web site. Table 1 lists the observations used in this paper. RXTE performed two 10 day sets of consecutive observations in 1996 and 1998, which enable us to study dip parameter modulations over a timescale of several days. Simultaneous observations by RXTE and XMM-Newton were also carried out in 2002 May.

X1916–053 was observed by XMM-Newton on 2002 September 25 for about 15 ks. These data were reduced through standard processing with SAS (the XMM-Newton Science Analysis System). All the instruments, including the MOS detector, pn detector, reflection grating spectrometers, and OM module, were used for this observation. Although the pn detector provided a higher count rate and better signal-to-noise ratio, it only detected four complete dips, whereas MOS observed five. In order to collect a greater number of dips for better statistics, we used the MOS data for dip phase analysis. The barycenter correction, which corrects the time system from satellite to the barycenter of the solar system, is important for the timing analysis of such a short orbital period. SAS provides the barycenter correction task barycen for the XMM-Newton data. After applying this correction, the data can then be used for further dip analysis.

X1916–053 was observed by ASCA on 1993 May 2 for about 67 ks and by ROSAT on 1992 October 17 for about 18 ks. Since FTOOLS provides the means to correct the time system, we downloaded the event files for ASCA and ROSAT. The barycenter correction for the ASCA data was produced by the task timeconv, while the ROSAT data used bct+abc. In addition, the event files from BeppoSAX observations were included in our analysis. The observation times were approximately 82 ks in 1997 and 98 ks in 2001. The data were barycenter-corrected with the FTOOLS task earth2sun, which can only correct for the time delay from Earth to the solar system barycenter.

The data collected by RXTE, Ginga, EXOSAT, Einstein, and OSO 8 were downloaded from HEASARC in light-curve format, already reduced through the corresponding standard processes. The additional column BARYTIME in the RATE light-curve data contains barycentered times corrected by the FTOOLS task fxbary. All the other data sets were barycenter-corrected with earth2sun only.

3. DATA ANALYSIS

3.1. Dip Parameters

Researchers have long been aware of variations in dip phase and width, as well as in other parameters (Yoshida et al. 1995; Chou et al. 2001; Homer et al. 2001). Unfortunately, dip profiles are usually complicated, and finding a unique set of parameters applicable to all dips is difficult. Taking the definition of a dip’s center as an example, Yoshida et al. (1995) defined dip center time as the midpoint of selected “start” and “end” times of a dip, but the value depends strongly on how one chooses the “start” and “end” times. On the other hand, Chou et al. (2001) defined dip center by fitting a dip with a quadratic curve around the point with minimum intensity. Homer et al. (2001) fitted dips with a Gaussian profile. However, none of these methods are suitable for dips with complex profiles, such as that in Figure 1. It is therefore necessary to extract dip properties with a new method that is not only independent of boundary selection but which can also be applied to all kinds of dip profiles, regardless of their complexity.

An X-ray dip is caused by absorption by the bulge in the accretion disk. We can first divide a light curve into dip states and persistent (nondip) states by roughly guessing the boundaries of the accretion disk. We can then divide each dip state into dip and persistent (nondip) states by roughly guessing the boundaries of dips (see Fig. 1). The observed count rate during the persistent state, $I_0$, when the bulge is far from the line of sight is estimated

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Here is the table from the text:

| Year   | Observatory | Observation Date | Number of Dips |
|--------|-------------|------------------|---------------|
| 2002   | XMM-Newton  | Sep 25           | 7             |
| 2001   | RXTE        | Sep 25           | 27            |
| 1998   | RXTE        | May 25, Jun 16, 17, 30, Jul 1, Oct 1 | 27 |
| 1997   | BeppoSAX    | Oct 1–2         | 9             |
| 1996   | RXTE        | Jun 24, Jul 17–26, Aug 1, 10, Sep 14, 16 | 26 |
| 1993   | ASCA        | May 2–3         | 5             |
| 1992   | ROSAT       | Oct 17–19       | 1             |
| 1990   | Ginga       | Sep 11–13       | 2             |
| 1988   | Ginga       | Sep 9–12        | 2             |
| 1985   | EXOSAT      | May 24, Oct 13  | 10            |
| 1983   | EXOSAT      | Sep 17          | 8             |
| 1980   | Einstein    | Oct 11          | 2             |
| 1979   | Einstein    | Oct 22          | 1             |
| 1978   | OSO 8       | Apr 7–14        | 1             |

* This column represents the number of dips for each year. However, some light curves containing no complete dips or having relatively lower significance are combined into one folded light curve, so that we treat them as a single dip per folded light curve.

*a* Simultaneous observation by RXTE and XMM-Newton.

Ten days of consecutive observations in both 1998 and 1996.
by fitting a straight line through neighboring persistent states. Much like calculating the gravitational center of an object, dip center time (or phase in the folded light curve) is the average of the dip times weighted by the difference between the dip state and the predicted persistent count rate:

$$t_{c} = \frac{\sum_{i=1}^{N} (I_{0} - I_{i})t_{i}}{\sum_{i=1}^{N} (I_{0} - I_{i})},$$

where $t_{i}$ and $I_{i}$ are the time and count rate of the $i$th bin, respectively. To evaluate the physical width of the dip, the dispersion is defined as

$$W = \left[ \frac{\sum_{i=1}^{N} (I_{0} - I_{i})(t_{i} - t_{c})^2}{\sum_{i=1}^{N} (I_{0} - I_{i})} \right]^{1/2},$$

which is equivalent to the second moment of the dip state. Analogously to the equivalent width in spectrographic analysis, the equivalent width of the dip, which can also be considered the strength of the dip, is

$$EW = \sum_{i=1}^{N} \frac{I_{0} - I_{i}}{I_{0}} \Delta t,$$

From the definitions above, as long as the boundaries reside in the persistent states neighboring the dip, the points that lie in a persistent state beside the dip make little contribution to the dip parameters (i.e., $I_{0} - I_{i} \approx 0$). The parameters are therefore insensitive to boundary selection for calculations. Furthermore, these three values are well defined regardless of the dip profile’s complexity. This method can also be applied to the eclipse source. The only constraint is that a completely observable dip or eclipse is required. In order to check whether the parameters are sensitive to the boundary choice, a test was performed on a dip that is hard to fit with a quadratic function (Chou et al. 2001) or a Gaussian (Homer et al. 2001), as shown in Figure 2. We set the left boundary ($i = 1$; see Fig. 1) at a fixed value and gradually changed the right boundary ($i = N$) from dip state to persistent state. The test results show that the derived parameters are insensitive to the right boundary.
boundary as long it resides well within the persistent state. A similar result was obtained with the right boundary fixed in the persistent state and a variable left boundary. We therefore conclude that our method is adaptable to dips of various profiles.

Simultaneous XMM-Newton and RXTE observations provide an opportunity to inspect whether the dip parameters are energy (or instrument) dependent. To test for energy dependence, the XMM-Newton events detected by the MOS detector were divided into a soft band (0.7–1.7 keV) and a hard band (1.7–8.0 keV) so that the available counts were roughly equal. Table 2 lists the parameters of the five dips in the MOS observation. There is no significant energy dependence to the dip dispersion, but the equivalent width is highly energy dependent, as expected given that the dip center time seems to have almost the same, but the energy dependence of the dip center times is marginally detected in the 1996 observation. The detection of dips are caused by absorption. The dip center time is measured from MJD(TDB) 52,542.

### TABLE 2

**Dip Parameters versus Energy Bands**

| Dip Number | Energy Band (keV) | Dip Center Time (s) | Dispersion (s) | Equivalent Width (s) |
|------------|------------------|--------------------|----------------|---------------------|
| 1........... | 0.7–8.0 (total)  | 15,619.323         | 193.476        | 444.308             |
|            | 0.7–1.7 (soft)   | 15,624.551         | 194.775        | 485.480             |
|            | 1.7–8.0 (hard)   | 15,616.351         | 192.344        | 431.547             |
| 2........... | 0.7–8.0 (total)  | 18,767.322         | 187.421        | 291.581             |
|            | 0.7–1.7 (soft)   | 18,766.314         | 191.611        | 341.541             |
|            | 1.7–8.0 (hard)   | 18,769.707         | 183.034        | 250.401             |
| 3........... | 0.7–8.0 (total)  | 21,771.504         | 223.684        | 415.795             |
|            | 0.7–1.7 (soft)   | 21,776.967         | 220.304        | 471.319             |
|            | 1.7–8.0 (hard)   | 21,765.254         | 227.488        | 370.354             |
| 4........... | 0.7–8.0 (total)  | 24,769.473         | 243.336        | 474.337             |
|            | 0.7–1.7 (soft)   | 24,771.145         | 245.808        | 541.436             |
|            | 1.7–8.0 (hard)   | 24,769.922         | 239.112        | 417.391             |
| 5........... | 0.7–8.0 (total)  | 27,723.248         | 250.468        | 457.142             |
|            | 0.7–1.7 (soft)   | 27,729.359         | 249.732        | 516.507             |
|            | 1.7–8.0 (hard)   | 27,716.568         | 249.946        | 404.874             |

**Note.**—Dip center time is measured from MJD(TDB) 52,542.

### 3.2. Periodicity of Dip Parameters

The new dip parameter definitions can be utilized to systematically study the variations of the parameters over a timescale of several days, which are likely due to the apsidal precession or nodal precession period of the accretion disk. Suitable data sets to search for periodicity are the 10 day consecutive RXTE observations from 1996 and 1998. For these two sets of observations, all dip parameters varied significantly over timescales of 2–5 days (see Figs. 3 and 4). Some of the parameters show strong periodic variations, especially the dispersion in the 1998 observations. The 1998 dip dispersions exhibit a sinusoidal-like modulation, with a period of $4.87 \pm 0.14$ days obtained from a sinusoidal fit (see Fig. 4). This is consistent with the results on marginal dip phase variation proposed by Homer et al. (2001). We further folded the dispersions of the entire 1998 RXTE data set with the 4.87 day period and found that all the observed dip dispersions in 1998 are coherent (see Fig. 5). This implies that the $\sim 4.87$ day modulation can stably last at least 2 months. A $\sim 4$ day period variation in the dispersion, close to the $\sim 3.9$ day period variation proposed by Chou et al. (2001), can be seen in the 10 day consecutive observations from 1996, although the periodicity is not as strong as for the dispersions in the 1998 data (see Fig. 3).

We also searched both data sets for the 3.9 and 4.87 day beat sidebands around the orbital period through an epoch-folding search. This was provided by the FTOOLS task efsearch. The 3.9 day sidebands are clearly seen, and the 4.87 day sidebands are marginally detected in the 1996 observation. The detection of 4.87 day sidebands is consistent with the negative superhump proposed by Ritter et al. (2002). Interestingly, no clear sideband was found in the 1998 data set, although the dip dispersion shows such periodicity.

### 3.3. Orbital Ephemeris

We collected all available dip center times from the X-ray light curves observed from 1978 to 2002 and applied the linear ephemeris proposed by Chou et al. (2001):

$$T_{\text{dip center}} = MJD(TDB) - 50,123,00944 + 1.4 \times 10^{-4} N + \frac{3000.6508 \pm 0.0009}{86,400}N$$

(4)

The dip phases were first rebinned yearly, and $a \pm 0.035$ phase error was assigned for phase jitter (see § 3.4). The long-term phase...
Evolution is shown in Figure 6. The linear ephemeris provided by Chou et al. clearly is not a good fit for these 24 years of phase evolution. The polynomial fits for the dip phase and time indicate that a quadratic fit ($\chi^2 > 0.75$, 11 degrees of freedom [dof]) is better than the linear one ($\chi^2 = 2.61$, 12 dof) at a confidence level greater than 99% from an $F$-test. This implies that the orbital period changed significantly with time from 1978 to 2002. No higher order term is required for the dip phase evolution, because the $F$-test confidence level in comparison with cubic ($\chi^2 > 0.72$, 10 dof) and quadratic fits is only 74%. We therefore updated the orbital ephemeris to a quadratic form,

$$TN = MJD(TDB) 50,123.00944 + 0.0004000007N + (2.67 \pm 0.56) \times 10^{-13}N^2,$$

and the period derivative is thus

$$\dot{P}_{\text{orb}}/P_{\text{orb}} = (1.62 \pm 0.34) \times 10^{-7}\text{ yr}^{-1}.$$

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$$TN = MJD(TDB) 50,123.00873 \pm 0.0004 + \frac{3000.6511 \pm 0.0007}{86.400}N + (2.67 \pm 0.56) \times 10^{-13}N^2,$$

and the period derivative is thus

$$\dot{P}_{\text{orb}}/P_{\text{orb}} = (1.62 \pm 0.34) \times 10^{-7}\text{ yr}^{-1}.$$
This positive value means that the orbital period has been increasing with time. Section 4.2 discusses further implications of this orbital change.

3.4. Stability of the Dips

When an accretion stream hits an accretion disk, a bulge forms near the impact region. However, the stream could penetrate the accretion disk and form a ringlike enhancement of the surface density. Frank et al. (1987) proposed a model with two “bulges”: One lies at the impact region of the inflow stream, at the accretion disk’s edge, at about 0.8–1.0 orbital phase relative to the companion star. Another bulge, made up of a two-phase medium of cold clouds and hot intercloud gas, forms on the disk ring between phase 0.3 and 0.8. This model can successfully explain the dips in the eclipsing low-mass X-ray binary (LMXB) EXO 0748–676. Most dips in this system concentrate around phases 0.65 and 0.9, which correspond to the two bulges in this model (Frank et al. 1987). X1916–053 has no eclipse with which to determine the companion star’s position as a reference point, so it is hard to verify the bulge locations responsible for primary and secondary dips (Smale et al. 1988). However, we believe that the bulge near the edge of the accretion disk is more stable than the inner bulge, because it is closer to the companion star and its location in the orbital frame is less affected by the accretion disk.

To verify the bulge locations responsible for the primary and secondary dips, we tested the phase fluctuations (jitters) for both kinds of dips. The dip phases folded on the best quadratic ephemeris obtained from the primary dips show that the standard deviation = 0.073) of the primary dips (0.035, 128 dips) is significantly smaller than that of the secondary dips (0.074), the mass ratio can be estimated as $q \sim 0.045$, slightly larger than the values proposed by Chou et al. (2001). All the models imply that the companion’s mass is less than the lower limit for a normal main-sequence star ($\leq 0.08 M_\odot$), consistent with the previous prediction that the

4. DISCUSSION

4.1. Nodal Precession and Negative Superhump

The negative-superhump signal of nodal precession was detected by Retter et al. (2002) in RXTE observations from 1996. They concluded that the signal was due to persistent-state modulation rather than variations in the dip width (or shape), because the signal still exists in the Lomb-Scargle power spectrum even when the dips are removed from the light curve. In our analysis, although the periodicities of the dip parameters are weak in the 1996 RXTE observations, the periodicity of the dip width variation in the 1998 RXTE observations is strong. This 4.87 day period, confirmed in §3.2, is consistent with Retter et al.’s result and provides more evidence of a negative superhump.

It is believed that a bulge lying on the outer edge of an accretion disk will be more opaque and of greater width near the disk plane. If the accretion disk has retrograde nodal precession, the angle between the disk plane and the observer’s line of sight will vary with the nodal precession period (see Fig. 6.18 of Hellier 2001). As a result, dip width variation can be interpreted easily as a variation in the angle of the disk plane. The 4.74 day dip phase variation proposed by Homer et al. (2001) may be induced by a dip width variation due to asymmetric bulge geometry.

The mass ratio of X1916–053 can be inferred from the negative-superhump period. Chou et al. (2001) derived a mass ratio of 0.022 or 0.011 for a 3.9 day positive superhump or a Roche lobe–filled white dwarf, respectively. On the other hand, for a negative superhump, Larwood et al. (1996) proposed that the relation between the nodal precession period of the disk and the particle frequency in the outer accretion disk can be expressed as

\[
\frac{\omega_n}{\Omega(R)} = -\frac{15}{32} q r^3 \cos \delta,
\]

where $\omega_n$ is the frequency of nodal precession, $\delta$ is the tilt angle of the accretion disk, $\Omega(R)$ is the particle frequency in the outer accretion disk, and a ratio of specific heats $\gamma = 5/3$ is assumed. For $\Omega(R) = 3 \omega_{\text{orb}}$ and assuming a small $\delta$, the mass ratio can be estimated as $q \sim 0.045$, slightly larger than the values proposed by Chou et al. (2001).
secondary must be a fully degenerate or semidegenerate white dwarf.

4.2. Orbital Period Change

Table 4 lists the six LMXBs with significant detections of orbital period changes prior to this research. Five of them (EXO 0748–676, 4U 1820–30, X1822–371, Cyg X-3, and SAX J1808.4–3658) have period derivatives inconsistent with the standard model proposed by Rappaport et al. (1987) (see Tavani 1991; Di Salvo et al. 2007). The standard model, in which mass loss and orbital period changes are due to gravitational radiation, predicts a positive orbital period derivative for LMXBs with degenerate companions. X1916–053 is an LMXB composed of a neutron star and a white dwarf. Using the Rappaport et al. model the orbital period derivative would be $P_{\text{orb}}/P_{\text{orb}} = 5.96 \times 10^{-10} \text{yr}^{-1}$, which is a factor of $10^2 - 10^3$ smaller than the observed value. The period derivative predicted by this model would be consistent with the observed value only if the mass transfer were extremely non-conservative (near the singularity in this model).

Tavani (1991) proposed a radiation-driven model to explain inconsistencies between the standard model and observed values, arguing that the companion star may be illuminated by a relatively large flux of radiation from the primary star or accretion disk. Such radiation can drive a strong evaporative wind from the companion’s outer atmosphere. In this model, the irradiated companion can transfer mass even if it does not fully fill its Roche lobe.

Tavani derived an average self-sustained rate of radiation-driven mass loss of $-\dot{m}_r \approx 10^{-6} M_\odot \text{yr}^{-1}$, which is much larger than that owing to gravitational radiation ($-\dot{m}_{GR} \approx 9.15 \times 10^{-12} M_\odot \text{yr}^{-1}$). For X1916–053, the value of the period derivative can be interpreted by this model with 60%–90% of the companion’s mass loss outflowing from the system. Such mass outflow has been detected in LMXBs. Chakrabarty et al. (1998) reported a strong He i 1.083 $\mu$m emission line with a P Cygni profile in GX 1+4 (V2116 Oph) through infrared observations. From the blue edge of this profile, they inferred that there is an outflow with a velocity much faster than a typical red giant wind from this binary system. For X1916–053, such an outflow could be verified if a P Cygni profile were detected in the optical counterpart. Unfortunately, the optical counterpart of X1916–053 is so dim ($V = 21$ mag) that no optical spectroscopy has ever been reported. From the mass accretion onto the neutron star predicted by Tavani (1991), the X-ray luminosity can be estimated as $(1 - 4) \times 10^{37} \text{ergs s}^{-1}$. This is slightly larger than the observed value $(0.5 - 1.44) \times 10^{37} \text{ergs s}^{-1}$; Blaes et al. 2000).

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### TABLE 4

Characteristics of LMXBs with Measured Orbital Period Change

| Object Name | Modulation | $P_{\text{orb}}$ (yr) | $P_{\text{orb}}/P_{\text{orb}}$ (yr) | Reference |
|-------------|------------|----------------------|---------------------------------|-----------|
| 4U 1820–30  | M          | 0.19                 | $3.74 \times 10^{-8}$           | Chou & Grindlay 2001 |
| X1916–053   | D          | 0.83                 | $1.62 \times 10^{-7}$           | This work |
| SAX J1808.4–3658 | M   | 2.01                 | $1.48 \times 10^{-8}$           | Di Salvo et al. 2007 |
| EXO 0748–676 | D, E      | 3.82                 | $2.7 \times 10^{-8}$            | Wolff et al. 2002 |
| Cyg X-3    | M          | 4.82                 | $1.05 \times 10^{-6}$           | Singh et al. 2002 |
| X1822–371   | PE, D      | 5.57                 | $3.4 \times 10^{-7}$            | Heller et al. 1990 |
| Her X-1     | E          | 40.8                 | $1.32 \times 10^{-8}$           | Deeter et al. 1991 |

* (E) Total eclipse; (PE) partial eclipse; (D) periodic dips; (M) other modulation.

* The period derivative for EXO 0748–676 comes from the quadratic fit to the entire data set from EXOSAT (1985) to RXTE (2000).

* Cyg X-3 is identified as a high-mass X-ray binary because the companion star has been confirmed to be a Wolf-Rayet helium star with a strong wind.