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Citation: Wang, Zhongxiang, and Deepto Chakrabarty. "DISCOVERY OF A 693.5 s PERIOD IN THE X-RAY BINARY 4U 1820 – 30: A SUPERHUMP INTERPRETATION." *The Astrophysical Journal* 712.1 (2010): 653–657. © 2012 IOP Publishing

As Published: <http://dx.doi.org/10.1088/0004-637X/712/1/653>

Publisher: IOP Publishing

Persistent URL: <http://hdl.handle.net/1721.1/75783>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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DISCOVERY OF A 693.5 S PERIOD IN THE X-RAY BINARY 4U 1820–30: A SUPERHUMP INTERPRETATION

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Draft version February 9, 2010

ABSTRACT

The X-ray source 4U 1820–30 in the globular cluster NGC 6624 is known as the most compact binary among the identified X-ray binaries. Having an orbital period of 685.0 s, the source consists of a neutron star primary and likely a 0.06–0.08 M_{\odot} white dwarf secondary. Here we report on far-ultraviolet (FUV) observations of this X-ray binary, made with the Space Telescope Imaging Spectrograph on board the *Hubble Space Telescope*. From our Fourier spectral analysis of the FUV timing data, we obtain a period of 693.5 ± 1.3 s, which is significantly different from the orbital period. The light curve folded at this period can be described by a sinusoid, with a fractional semiamplitude of 6.3% and the phase zero (maximum of the sinusoid) at MJD 50886.015384 \pm 0.000043 (TDB). While the discovered FUV period may be consistent with a hierarchical triple system model that was previously considered for 4U 1820–30, we suggest that it could instead be the indication of superhump modulation, which arises from an eccentric accretion disk in the binary. The X-ray and FUV periods would be the orbital and superhump periods, respectively, indicating a 1% superhump excess and a white-dwarf/neutron-star mass ratio around 0.06. Considering 4U 1820–30 as a superhump source, we discuss the implications.

Subject headings: binaries: close — stars: individual (4U 1820–30) — X-rays: binary — stars: low-mass — stars: neutron

1. INTRODUCTION

Among the known X-ray binaries (XRBs) that consist of an accreting neutron star (NS) or black hole primary, the NS binary 4U 1820–30 in the globular cluster NGC 6624 is known as the most compact binary (e.g., Ritter & Kolb 2009): its orbital period $P_{\text{orb}} = 685.0119 \pm 0.0001$ s (Stella, Priedhorsky, & White 1987; Chou & Grindlay 2001). Considering this short period, the Roche-lobe filling companion in the binary can be estimated to be a 0.06–0.08 M_{\odot} , hydrogen-exhausted white dwarf (WD; Rappaport et al. 1987). The X-ray source shows a long-term modulation with a period of approximately 171 days (Priedhorsky & Terrell 1984a; Chou & Grindlay 2001; Zdziarski et al. 2007), which was interpreted as an indication that this source is a hierarchical triple system (Grindlay 1988; Chou & Grindlay 2001). In this triple system model, the NS-WD binary is the inner binary with orbital period $P_{\text{inner}} \approx 685$ s, and a second companion, orbiting the inner system with a period of $P_{\text{outer}} \sim 1$ day, induces an inner-binary eccentricity variation with the 171 day period. Consequently, the mass accretion rate and X-ray luminosity of the X-ray source modulate with the same period.

In this paper, we report on the detection of a periodicity in 4U 1820–30 from far-ultraviolet (FUV) observations, made with the *Hubble Space Telescope* (HST). This FUV period is about 1% longer than the X-ray period, a difference that approximately fits the triple system model: one of the two periods, either the X-ray or FUV, is P_{inner} , while the other one is the beat period between P_{inner} and P_{outer} . However, since a very similar source, the XRB 4U 1916–05 (which has X-ray

and optical periods of 50.00 min and 50.46 min, respectively), has been verified as a superhump source by the detection of negative superhumps in X-ray observations (Retter et al. 2002 and reference therein), the slightly longer FUV period detected in 4U 1820–30 could well be the indication of the binary also being a superhump source. Additionally, a long term modulation (199 day) in the X-ray light curve of 4U 1916–05 had also been reported (Priedhorsky & Terrell 1984b; Smale & Lochner 1992), although Homer et al. (2001) only found a likely 83 day modulation. Due to the similarities between the two sources, we thus suggest a superhump model for 4U 1820–30 in this paper.

Superhumps are periodic modulations observed in interacting binary systems with periods a few percent longer than their orbital periods. This phenomenon was first discovered in the super-outbursts of the dwarf nova VW Hyi (Vogt 1974; Warner 1975), and since then, it has been commonly detected in short-period cataclysmic variables (e.g., Patterson 1998; Skillman et al. 1999). It is generally believed that superhumps arise from an elliptical accretion disk, which is developed when the disk extends beyond the 3:1 resonance radius and precesses in the inertial frame due to the tidal force of a secondary star (e.g., Whitehurst & King 1991). The resonance condition—the mass ratio of a secondary to a primary $q \lesssim 0.33$ —appears to also work in X-ray binaries, as superhumps have been detected in both black hole soft X-ray transients (SXTs; O’Donoghue & Charles 1996) and NS XRBs 4U 1916–053 and GX 9+9 (Haswell et al. 2001). Indeed, Haswell et al. (2001) have further suggested that NS low-mass XRBs with orbital periods below ~ 4.2 hr are potential superhump sources.

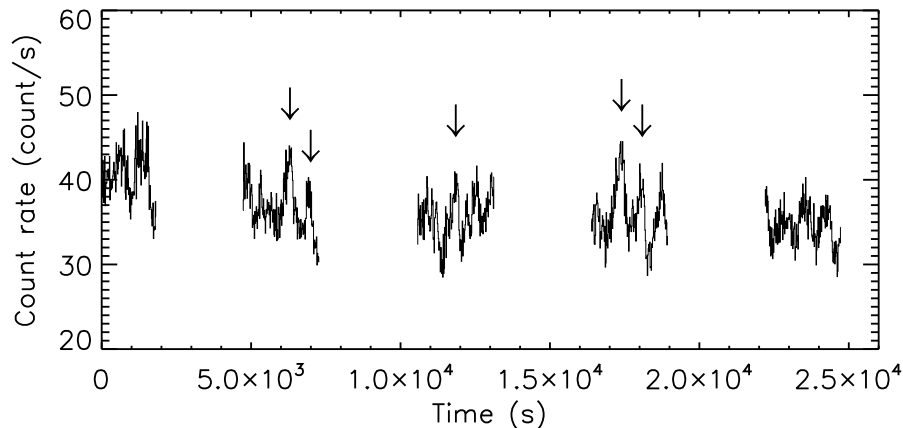


FIG. 1.— *HST*/STIS FUV light curve of 4U 1820–30. For clarity, the photon counts are binned in 16 s time intervals. A modulation is clearly visible in the light curve. The modulation peaks that are used in the data analysis in § 3 are marked by arrows.

Previous ultraviolet (UV) observations of 4U 1820–30, made with the former *HST* instrument Faint Object Spectrograph (FOS) in RAPID mode (in a wavelength range of 1265–2510 Å), revealed a periodic modulation with a 16% amplitude (Anderson et al. 1997). Although the reported UV period, 687.6 ± 2.4 s, is consistent with the X-ray period, the accuracy of the timing result should have been hampered by several uncertainties on FOS timing in RAPID mode (for details, see FOS Instrument Science Report CAL/FOS #124, #150)¹.

2. OBSERVATIONS AND DATA REDUCTION

The *HST* observations were made on 1998 March 14 using the Space Telescope Imaging Spectrograph (STIS; Woodgate et al. 1998). A low-resolution grating G140L was used with the solar-blind CsI multi-anode microchannel array (STIS/FUV-MAMA) detector, providing an FUV wavelength coverage of 1150–1730 Å and a plate scale of $0.025''/\text{pixel}$ along the spatial direction. The aperture used was a $52'' \times 0.5''$ long slit. The data were taken in TIMETAG mode, recording the detector position and arriving time of each detected photon. The timing resolution was 0.125 ms. We obtained the data from the *HST* archive service. The datasets consist of five exposures with a total exposure time of 12.1 ks: the first dataset had an exposure time of 1830 s, while the exposure time for each of the other four was 2580 s. The total time span was $T_s \approx 24.7$ ks ($\simeq 7$ hrs).

Using the IRAF task `odelaytime` in the *HST* calibration package STIS, we applied a barycenter correction to the measured arrival times. The *HST* ephemeris (ORX) file at the observation time was obtained using the `Starview` program. A box region with a 30-pixel ($=0''.75$) width in the spatial direction, which well covered the target’s spatial profile, was used for collecting the target’s counts. We excluded the counts within the Ly α $\lambda 1216$ Å line, for which the source was strong background emission (Anderson et al. 1997). The resulting light curve of 4U 1820–30 is shown in Figure 1. A modulation is clearly visible in the light curve. The contam-

ination from the background was limited: in a nearby region with the same size to that of the target region, we found a background count rate of only $1.3 \text{ counts s}^{-1}$ (compared to $30\text{--}45 \text{ counts s}^{-1}$ in the target region).

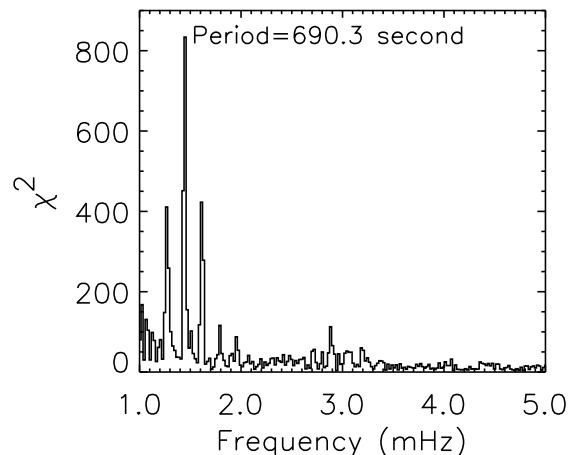


FIG. 2.— Result of the epoch-folding analysis. A period of 690.3 s is clearly detected. Two major sidebands are artifacts due to the observation gaps.

3. RESULTS

We first used an epoch-folding technique (Leahy et al. 1983) to search for periodicity, with the data folded to 10 phase intervals per period. The resulting χ^2 values are shown in Figure 2, clearly indicating the detection of a periodicity. The period is $P = 690.3$ s, 5.3 s longer than the 685.0 s X-ray period. However, based on the epoch-folding technique, the frequency spacing was $1/2T_s = 2.02 \times 10^{-5}$ Hz, corresponding to a temporal spacing of 9.6 s near 690 s. As a result, the spacing is not sufficient to determine the period difference between 690.3 s and 685.0 s.

To more accurately determine the period, we 10 times over-sampled our data and used a discrete Fourier transform technique to construct an over-resolved power spec-

¹ http://www.stecf.org/poa/FOS/fos_bib.html

trum (e.g., Chakrabarty 1998; Ransom et al. 2002). The original data were binned evenly in 1-s time intervals for the Fourier transform. In Figure 3, the over-resolved power spectrum in the vicinity of the main power peak is shown. We fit the peak with a Gaussian to obtain the peak frequency, and found $f = 1.4442 \pm 0.0027$ mHz, corresponding to a period of 693.5 ± 1.3 s, where the standard 1σ uncertainties for signal frequency in an over-resolved power spectrum are given (Middleditch & Nelson 1976; Ransom et al. 2002). This indicates that the period difference between the FUV and X-ray periods is significant (approximately $6\sigma_P$ confidence).

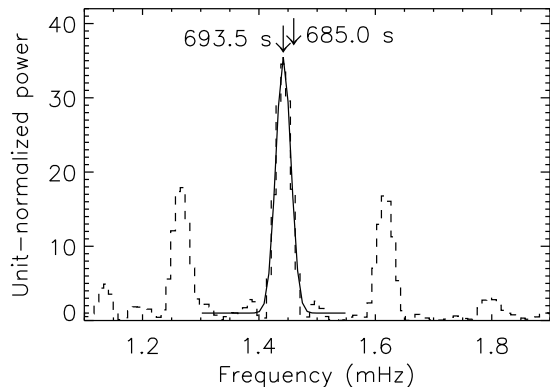


FIG. 3.— A 10 times over-resolved power spectrum (dashed curve) in the vicinity of the main power peak, resulting from the discrete Fourier transform. Two major sidebands are artifacts due to the observation gaps. Fitting the peak with a Gaussian function (solid curve), the peak frequency is found to be $f = 1.4442 \pm 0.0027$ mHz (or 693.5 ± 1.3 s). The frequency position of the X-ray period 685.0 s is also indicated.

Careful examination of the light curves in Figure 1 reveals that the strongest modulation peaks are asymmetric and non-sinusoidal in shape. As an additional check on our determination of the modulation period, we also used a phase-dispersion minimization technique (Stellingwerf 1978). This technique works well for cases of non-sinusoidal variation contained in a few irregularly spaced observations. The resulting periodogram in the vicinity of the minimum Θ statistic is shown in Figure 4. Fitting the region near the minimum with a parabola (Stellingwerf 1978), we found $P = 693.3$ s. The period value, again deviating from 685.0 s, is consistent with that obtained from the Fourier transform.

In order to quantify the overall periodic modulation in the light curve and thereby compare it with that obtained by Anderson et al. (1997), we binned the data in 10 s time intervals and obtained 1215 data points. The data points in each exposure interval were subtracted and normalized by the average, and then folded at the period of 693.5 s. The folded data points, shown in the top panel of Figure 5, are scattered in a relatively large range. For example, further binning the folded data points into 10 phase bins, the standard deviations of the bins were found to be between 5.9–8.4%. Large scattering in optical light curves of XRBs is commonly seen (e.g., Wang et al. 2009). For our case, we note that the modulation amplitude has significant variations in the data (Figure 1). For example, in several regions, the modulation is barely visible. These amplitude variations

smear the periodic modulation and cause large scattering in the folded light curve.

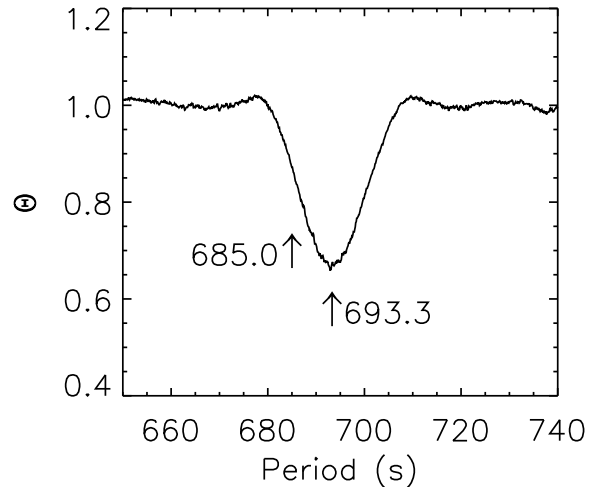


FIG. 4.— Phase dispersion minimization periodogram in the vicinity of the minimum Θ statistic. The positions of the minimum Θ statistic and X-ray period 685.0 s are marked by arrows to indicate their difference.

Following Anderson et al. (1997), we fitted a sinusoid to the 1215 data points, with the period fixed at 693.5 s. The best-fit has reduced $\chi^2 = 1.9$ for 1212 degrees of freedom, reflecting large scattering of the data points. From the best-fit, we found a semiamplitude of 6.3%. The time at the maximum of the sinusoidal fit (phase zero) was MJD 50886.015384 \pm 0.000043 (TDB) at the solar system barycenter. This semiamplitude we obtained is 2% lower than that in the UV range reported by Anderson et al. (1997). This difference could be due to the different wavelength coverages, because while the time spans of the UV and FUV data were approximately equal, the former covered a wavelength range twice as large as the latter. In addition, the UV observations were made in 1996, two years earlier than the FUV observations. Therefore the difference could also be due to intrinsic variations in UV emission from the source.

The strong modulation peaks are asymmetric. Here we folded 5 such peaks to show the asymmetry feature. In Figure 1, the peaks that were used in folding are marked by arrows. The folded light curve is shown in the bottom panel of Figure 5. As can be seen, the light curve has a slow rise and a fast decline, with a semiamplitude of $\simeq 10\%$. This asymmetric modulation is different from those sinusoidal or double-hump modulations that arise from companion stars and normally seen in XRBs (e.g., van Paradijs & McClintock 1995). Rather, it resembles those modulations seen in superhump sources (e.g., Retter et al. 1997).

4. DISCUSSION

Using different techniques in our timing analysis, we have discovered a period that is significantly different from the X-ray period. X-ray observations of 4U 1820–30 by various X-ray observatories have consistently obtained the 685.0 s period over the

past two decades (e.g., Smale, Mason, & Mukai 1987; Morgan, Remillard, & Garcia 1988; Sansom et al. 1989; Tan et al. 1991; van der Klis et al. 1993b; Chou & Grindlay 2001), demonstrating the stableness of the X-ray period. Also even though an X-ray period derivative \dot{P} has been detected (Tan et al. 1991; van der Klis et al. 1993b; Chou & Grindlay 2001), its negative value, $\dot{P}/P \approx -(2-5) \times 10^{-8} \text{ yr}^{-1}$, not only implies a decrease of the period as a function of time, but also is too small ($\Delta P \leq 0.035 \text{ ms yr}^{-1}$) to account for any period changes comparable to the 8.5 s difference between the X-ray and FUV periods. As STIS may be repaired in the future, our result could be confirmed by further observations. We would use a phase-coherent timing technique to build a long time span from several short observations, thus allowing a very accurate determination of the FUV period (e.g., Wang et al. 2009).

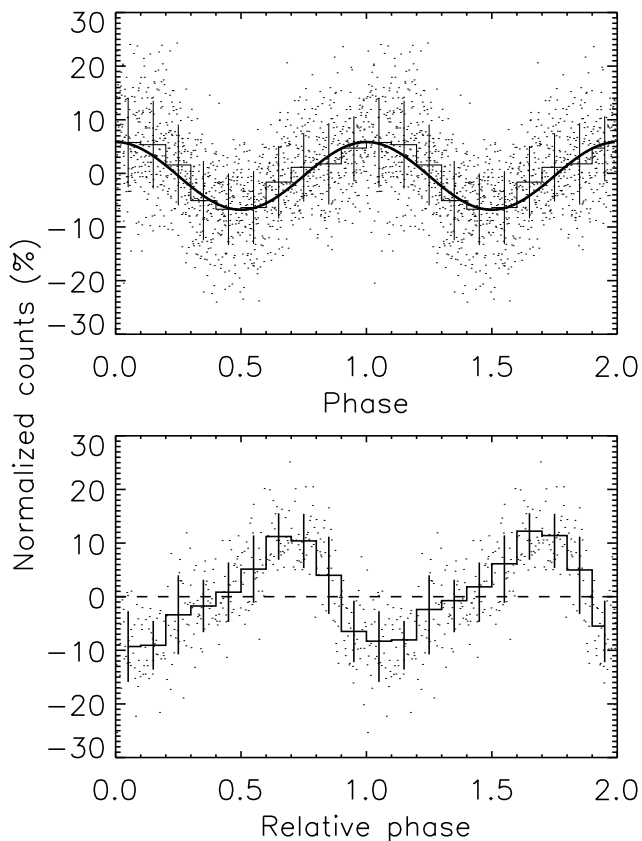


FIG. 5.— *Top panel*: normalized photon counts (relative to the mean) folded with the 693.5-s period. Two cycles are displayed for clarity. The solid curve indicates the best-fit sinusoid that has a semi-amplitude of 6.3%. However, the data points are scattered in a relatively large range, indicated by the 5.9–8.4% standard deviations (error bars) of the bins (histogram line); each bin is the average of the data points within 0.1 phase. *Bottom panel*: same as the top panel, but only photon counts contained in the strong modulation peaks (see Figure 1) are used in folding.

The discovered period could be additional evidence for the triple system model, which has been suggested for 4U 1820–30 (Grindlay 1988; Chou & Grindlay 2001). Since the source is located near the center of the globular cluster (King et al. 1993), the existence of triple systems is expected due to binary-binary interactions (e.g.,

Rasio, McMillan, & Hut 1995). Indeed, one triple system, known as PSR B1620–26, has been found in the globular cluster M4, although this source may not represent a prototypic triple system in a globular cluster (Sigurdsson & Thorsett 2005). The second companion around the system’s inner NS-WD binary is a Jovian planet (Sigurdsson et al. 2003).

However, given the similarities between the XRBs 4U 1820–30 and 4U 1916–053, it is likely that 4U 1820–30 is a superhump source with the X-ray and FUV periods being P_{orb} and the superhump period P_{sh} , respectively. Since the orbital periodicity is indicated by dips in the X-ray light curve of the source, this XRB probably has an inclination angle of $\sim 60^\circ$ (van Paradijs & McClintock 1995). With this angle, the UV modulation that is caused by X-ray irradiation of the companion star has been estimated to be at the 5% level of the persistent emission from the accretion disk (Arons & King 1993). The superhump modulation, presumably reflecting the area changes of the X-ray irradiated accretion disk, could be comparable but slightly stronger (Haswell et al. 2001). Therefore the FUV modulation we detected could arise from both the companion and disk, but with the latter slightly dominant over the former. This might explain large scattering seen in the folded light curve. In addition, the strong modulation peaks in the light curve appears to be asymmetric, resembling those seen in superhump sources. This asymmetry feature in the modulation provides additional support to our suggestion that 4U 1820–30 is a superhump source. The origin of the long-term 171 day variation is not clear. Simply by comparison, it would be the so-called “superorbital” modulation since long-term periodicities have been seen in a few other XRBs. This type of modulations has been suggested to be caused by the nodal precession of a warped disk (e.g., Clarkson et al. 2003). However, critical questions remain to be answered for the warping disk scenario (e.g., Clarkson 2003; Zdziarski et al. 2007).

In the superhump model, the superhump excess is defined as $\epsilon = (P_{\text{sh}} - P_{\text{orb}})/P_{\text{orb}}$. For 4U 1820–30, we obtain $\epsilon \approx 0.012 \pm 0.002$, similar to those values found for 4U 1916–053 (Haswell et al. 2001) and SXTs (O’Donoghue & Charles 1996). Based on a relation between the superhump excess and mass ratio q (Patterson et al. 2005), $\epsilon = 0.18q + 0.29q^2$, it can be found that $q \approx 0.06$ for 4U 1820–30, implying a companion mass of about $0.08 M_\odot$ (a $1.4 M_\odot$ standard neutron star mass is assumed). This mass value is consistent with the mass range estimated for 4U 1820–30 in a standard scenario (i.e., the mass transfer in the binary system is driven by gravitational radiation; Rappaport et al. 1987).

It is interesting to note that the ϵ - q relation could be used to set a constraint on the mass of a neutron star if the mass of a companion could be estimated from other measurements. Currently, three distinct binary evolution channels are thought to form ultracompact binaries (whose orbital periods are less than ≈ 80 min; for ultracompact binary formation and evolution, see Deloye et al. 2007 and references therein). Assuming the WD channel for the formation of 4U 1820–30, the helium WD in this XRB would likely have a mass of 0.06 – $0.1 M_\odot$ at the present time, having evolved from an initial mass of 0.1 – $0.3 M_\odot$ at the beginning of the

XRB phase (Deloye et al. 2007; Deloye 2009, private communication). The q value estimated from the superhump period suggests that the accreting neutron star in 4U 1820–30 has a mass value not much larger than $1.4 M_{\odot}$, the canonical neutron star mass.

The observed negative \dot{P} has been a puzzling feature in 4U 1820–30 (van der Klis et al. 1993b; Chou & Grindlay 2001), since in the standard scenario, a positive \dot{P} for 4U 1820–30 is expected (Rappaport et al. 1987). The negative value could be caused by the gravitational acceleration of the globular cluster (Tan et al. 1991; van der Klis et al. 1993b; King et al. 1993). Alternatively as suggested by van der Klis et al. (1993a), the period changes could be caused by azimuthal variations of the impact point in the accretion disk (at which the gas flow from the companion star impinges on the disk), and the azimuthal variations could be induced by the precession of an elliptical accretion disk. As a result, the phase of the observed X-ray light curve would be shifted and thus there might not be any changes for the true orbital period (however, see Chou & Grindlay 2001 for arguments against this scenario). Our identification of 4U 1820–30 as a superhump source may provide a support to this scenario, since the accretion disk in a superhump source is expected to be elliptical.

In order to confirm whether 4U 1820–30 is a superhump system, critical evidence such as the detection of negative superhumps is required (Retter et al. 2002). According to the empirical relation among the periods of the negative and positive superhump and

orbit given by Olech et al. (2009), the negative superhump period should be ~ 678 s. We may also search for a beat period between the X-ray and FUV/optical periods from 4U 1820–30, since such a period was found from the X-ray light curve of 4U 1916–05 (3.90 days; Chou, Grindlay, & Bloser 2001; Homer et al. 2001). This beat period indicates that an accretion disk precesses with a period $P_{\text{prec}} = (1/P_{\text{orb}} - 1/P_{\text{sh}})^{-1}$. For 4U 1820–30, we estimate $P_{\text{prec}} \approx 0.7 \pm 0.1$ day. However, because the X-ray timing observations of 4U 1820–30 were mainly made with *Rossi X-Ray Timing Explorer (RXTE)*, searches for such a period are difficult because of ~ 1 day observation gaps of *RXTE* data. We note that our FUV observations were made near the bottom flux of the 171 day periodic modulation. In the superhump scenario, both the superhump and superorbital modulations are supposed to arise from the accretion disk in 4U 1820–30. A detection of any correlations between these two modulations, such as variations of the superhump period and light curve as a function of superorbital phase (van der Klis et al. 1993a), would verify the disk origin of the modulation and thus support that 4U 1820–30 is a superhump source.

We thank Jennifer Sokoloski for advice on timing analysis, Michael Nowak for a helpful discussion, and the anonymous referee for valuable suggestions. We also thank Lars Bildsten, Chris Deloye, and Andrzej Zdziarski for useful comments on an earlier version of

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