The Astrophysical Journal, 658:514–519, 2007 March 20

PULSATIONS DETECTED FROM ACCRETING HIGH-MASS X-RAY BINARIES AT LOW LUMINOSITIES

Robert E. Rutledge,[1] Lars Bildsten,[2] Edward F. Brown,[3] Deepto Chakrabarty,[4]
George G. Pavlov,[5] and Vyacheslav E. Zavlin[6]
Received 2005 October 7; accepted 2006 October 12

ABSTRACT

We report the detection of pulsations from two accreting transient high-mass X-ray binaries (HMXBs) at low X-ray luminosities ($\approx 1-4\times10^{34}$ ergs s^{-1}). While one (4U 1145−619) has been detected pulsing previously at a lower luminosity, the second (1A 1118−615) has not, making it the third such transient HMXB from which pulsations are detected at low luminosity. The pulsars exhibit broadband rms variability (22.3% ± 0.1% and 9.2% ± 0.1%, respectively). While the present observations do not permit measurement of a spin frequency derivative, spin-down is implied in comparison with previous *Compton Gamma Ray Observatory*/BATSE observations. If spin-down occurred at the presently observed X-ray luminosity of 4U 1145−619, the required mass accretion rate is insufficient to produce the observed X-ray luminosity from a shock at the magnetosphere, and only a fraction of the mass accretion makes its way to the neutron star surface, with most of the mass leaving the system, carrying away angular momentum to affect spin-down.

Subject headings: pulsars: general — pulsars: individual (4U 1145−619, 1A 1118−615)

1. INTRODUCTION

Pulsations detected from high-mass X-ray binaries (HMXBs) permit determination of the orbital elements of the neutron star (NS). Systems which are X-ray persistent, with luminosities $\gtrsim10^{37}$ ergs s^{-1}, typically have all orbital parameters characterized.

In contrast, transient HMXBs have X-ray luminosities that are typically low ($\lesssim10^{35}$ ergs s^{-1}), until the NS reaches periastron, where a short X-ray outburst is observed (~days). There are no systems in which the orbital elements are known, with the exception of the orbital period when a periodicity in the X-ray outburst is exhibited. Pulsations detected from these systems over the entire period of their orbits would permit sensitive determination of their orbital elements and inferences about their evolutionary status, informing scenarios for their formation and population synthesis.

Searches for pulsed emission from accreting NSs in HMXBs at low luminosities have been mostly unsuccessful. An observation with *ROSAT*/PSPC of 66 s period pulsar Cep X-4 at $L_X\approx3.2\times10^{32}$ ergs s^{-1} reported no evidence of pulsations (Schulz et al. 1995). Observations of three HMXBs (A0538-66, 4U 0115+63, and V0332+53) with *BeppoSAX* detected no pulsations at their known periods of 0.07, 3.62, and 4.37 s, while at log[L_X (ergs s^{-1})$^{-1}$] of 35.3, 33.0, and 32.7, respectively (Campana et al. 2002). Although the $P_{\rm pulse}=440$ s pulsar 4U 1907+09 has been detected persistently at luminosities as low as 3×10^{33} ergs s^{-1} $(d/2\ {\rm kpc})^2$ and 5×10^{34} ergs s^{-1} $(d/2\ {\rm kpc})^2$ using *ASCA* (Roberts et al. 2001), it is not clear whether this emission was pulsed.

However, pulsations from the 103 s pulsar A0535+26 have been previously detected, while the source luminosity was $\approx(3.5-4.5)\times10^{33}$ ergs s^{-1} (3–20 keV) during two *RXTE* observations, in which the spectrum was soft ($\alpha=2.6\pm0.2$ and 3.2 ± 0.3, where α is the photon power-law slope; Negueruela et al. 2000). A cyclotron absorption feature at 47 ± 2 keV reported by Kretschmar et al. (2005), Wilson & Finger (2005), and Inoue et al. (2005) confirms an earlier *Mir-Kvant*/TTM+HEXE low-significance detection ($\lesssim3\ \sigma$), corresponding to a magnetic field strength of $B=4.7\times10^{12}(1+z)$ G. Assuming this to be due to a dipolar surface magnetic field, the magnetospheric radius is $r_m=5.8\times10^9$ cm (Davidson & Ostriker 1973 their eq. [19]). This meets the criterion for the "propeller effect" (Illarionov & Sunyaev 1975; Stella et al. 1986) in which centrifugal inhibition of accretion interacting with the magnetic field at r_m results in matter being expelled from the system, when $r_m>r_{\rm co}$. Nonetheless, X-ray pulsations were detected near the known pulse period, implying either the propeller mechanism was <100% efficient and some fraction of the mass accretion at the magnetosphere found its way to the NS surface, or X-ray pulsations are produced from interaction between the rotating magnetic field and accretion at the magnetosphere.

Pulsed emission from 4U 1145−619 was previously observed in 1979 July ($F_X=8.6\pm2.0\times10^{-12}$ ergs cm^{-2} s^{-1}, 0.2–2 keV; $P_{\rm pulse}=290\pm2.0$ s), 1980 August ($F_X=6.0\pm0.5\times10^{-12}$ ergs cm^{-2} s^{-1}; $P_{\rm pulse}=291.5\pm1.0$ s), 1980 February ($P_{\rm pulse}=289\pm2$ s), and 1983 June ($F_X=50\pm2\times10^{-12}$ ergs cm^{-2} s^{-1}; $P_{\rm pulse}=291.1\pm1$ s) using *Einstein*/IPC (first three observations) and *EXOSAT*/LE (Mereghetti et al. 1987).

We report here the detection of pulsations from two HMXBs (4U 1145−619 and 1A 1118−615) at low luminosities ($L_X\lesssim10^{35}$ ergs s^{-1}), making the latter the third such HMXB to exhibit pulsations at low luminosities, after A0535+26 and 4U 1145−619. Short-term variability ($\lesssim$20,000 s) in both sources makes clear that accretion remains active at these luminosities. The present observations demonstrate that accretion powers the X-ray pulsars as well.

4U 1145−619 is a ≈292 s transient pulsar associated with a B1 Vne star (V801 Cen; Bradt et al. 1977; Dower et al. 1978). The X-ray source exhibits outbursts periodically, at 186.5 day intervals, likely the binary orbital period (Watson et al. 1981; Priedhorsky

[1] Department of Physics, McGill University, Montreal, QC, Canada; rutledge@physics.mcgill.ca.
[2] Kavli Institute for Theoretical Physics and Department of Physics, University of California, Santa Barbara, CA; bildsten@kitp.ucsb.edu.
[3] Department of Physics and Astronomy, Michigan State University, East Lansing, MI; ebrown@pa.msu.edu.
[4] Department of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA; deepto@space.mit.edu.
[5] The Pennsylvania State University, University Park, PA; pavlov@astro.psu.edu.
[6] Space Science Laboratory, NASA MSFC SD50, Huntsville, AL; vyacheslav.zavlin@nasa.msfc.gov.

TABLE 1
Observational and Source Characteristics

Parameter	4U 1145−619	1A 1118−615
Instrument	ACIS-S3	ACIS-S3
Start time (UT)	2002 Dec 29 16:28:34	2003 Aug 21 07:58:56
$T_{\rm integration}$ (s)	22672.4	18519.6
$T_{\rm observation}$ (s)	22963.2	19605.4
$T_{\rm resolution}$ (s)	3.24104	0.74014
$\Delta\nu_{\rm obs}$ (Hz)	4.35479×10^{-5}	5.10064×10^{-5}
Source (counts s^{-1})	0.675(5)	0.213(3)
Background (counts s^{-1})	0.0023	0.002
Estimated pileup	20%	<3%
R.A. (J2000.0)	$11^h48^m0.03^s$	$11^h20^m57.19^s$ ($\pm1''$)
Decl. (J2000.0)	$-62^\circ12'25.1''$	$-61^\circ55'0.2''$ ($\pm1''$)
Distance (kpc)	1.0	5.0
Spectral Measurements		
$\alpha_{\rm pileup}$	1[a]	<0.05
$N_{\rm H,\,22}$	0.215 ± 0.005	1.4 ± 0.1
$\alpha_{\rm photon}$	0.78 ± 0.01	1.6 ± 0.1
F_X (ergs cm^{-2} s^{-1}, 0.5–10.0 keV)	2.6×10^{-10}	3.9×10^{-12}
F_X (unabsorbed)	2.7×10^{-10}	5.9×10^{-12}
L_X (ergs s^{-1}, 0.5–10 keV)	3.3×10^{34}	1.8×10^{34}
Timing Measurements		
ν_p (mHz)	3.397(1)	2.444(5)
[b]$\rm rms_{pulse}$ (%)	22.3 ± 0.6	9.2 ± 0.3
$\alpha_{\rm LFN}$	0.61 ± 0.14	(0.6)
$\rm rms_{LFN}$(0.00005–0.1)	17 ± 3	20^{+4}_{-6}
Dead time correction factor	1.16 ± 0.03	1.025 ± 0.005

[a] Although a pileup model was implemented, the model was clearly inadequate to accurately extract the intrinsic spectrum at the observed flux; thus, $\alpha_{\rm pileup}$ is an upper limit.
[b] $\rm rms_{pulse}$ is not corrected for dead time, and therefore acts as a lower limit.

& Terrell 1983). Prior to the observation described here (MJD 52637), X-ray outbursts detected with *RXTE* /ASM (Levine et al. 1996) were observed, ending ≈MJD 50371 (the last day of >3 consecutive daily average count rates >3 σ above zero), 50555, 50925, and 51292. These dates are consecutively separated by approximately $n \times 186.5$ days, with $n \approx 1$, 2, and 2, further strengthening association of the outburst time scale with the orbital period.

No detailed information of the neutron star's orbit (ellipticity, orbital velocity, angle of periastron) is known for 4U 1145−619. An X-ray pulse timing study during outburst (Cook & Warwick 1987) concluded that pulsar spin-up was much greater than might be expected from accretion theory, and hypothesized that this could be explained by orbital motion if the eccentricity is >0.6 (Cook & Warwick 1987).

Optical study of the companion (Stevens et al. 1997) derived an effective temperature $(2.55 \pm 0.15) \times 10^4$ K, a bolometric magnitude of $M_{\rm bol} = -5.6 \pm 0.5$ at a distance 3.1 ± 0.5 kpc and a radius of 8 ± 2 $R_\odot$ for a 13 ± 2 $M_\odot$ star. A 1 σ distance range of 300–1000 pc has been derived from *Hipparcos* data (Chevalier & Ilovaisky 1998). It is unclear why the spectroscopic and parallactic distances differ by a factor of ≈3. We adopt a fiducial distance of 1.0 kpc for 4U 1145−619.

The 405 s pulsar 1A 1118−615 is associated with a O9.5 III–Ve star (He 3–640) with a derived distance of 5 ± 2 kpc (Janot-Pacheco et al. 1981). The orbital period of the binary is not known. The ≈16 yr period between X-ray outbursts may indicate the NS does not interact strongly with the massive companion at any time during its orbit (Villada et al. 1999). Previous optical observations (Polcaro et al. 1993) show dense material with an expansion velocity of 1350 km s^{-1}, soon after its 1992 January outburst, which was not present during a preoutburst observation. 1A 1118−615 has been detected previously at $L_X = 0.5\text{–}3 \times 10^{34}$ $(d/4\ {\rm kpc})^2$ ergs s^{-1} with the *EXOSAT*/ME instrument (Motch et al. 1988) and with the *Einstein*/IPC. No pulsations were reported during this observation.

No cyclotron line has been identified from either 4U 1145−619 or 1A 1118−615 (see Heindl et al. 2004 for a review of cyclotron lines), so no estimate of their magnetic field strength exists. Both sources were detected as episodic pulsed emission with BATSE (Bildsten et al. 1997).

In § 2 we describe the observations and analysis. In § 3 we discuss some possible implications of our analysis results, and we conclude in § 4.

2. OBSERVATIONS AND ANALYSIS

Our observations were made using the Advanced Chandra Imaging Spectrometer (ACIS-S; Garmire et al. 2003) on the *Chandra X-Ray Observatory.* Details of these observations are listed in Table 1. The instrument configurations for both observations were ACIS-S3 in imaging mode. Data were analyzed using CIAO v3.0.1. The observations were uninterrupted. Pointing for both was set off-axis by 4′ to mitigate pileup, although the observed fluxes were somewhat higher than predicted, and pileup is a serious hindrance for the data from 4U 1145−619. The X-ray point sources were localized using standard analysis; their positions are given in Table 1, and are consistent with the previously identified optical counterparts. We extracted X-ray counts within 7.5″ of the source. Background was negligible (<1%) compared to the observed count rates, and so we neglect it.

2.1. *Timing Analysis*

Barycenter corrections were applied using JPL DE405 solar system ephemeris. To produce the power density spectra (PDS; Press et al. 1995), we performed a Fourier transform (FT) of the discrete data using FFTW (Frigo & Johnson 1998), obtaining a FT with frequency resolution $\Delta\nu_{\rm obs} = 1/T_{\rm obs}$ (Table 1).

The pulsed power is evident near the frequencies at which the pulsars have been detected in outburst. The power (P) normalized according to Leahy et al. (1983), the chance detection probability of the pulsed power at the frequencies observed (see below) are $\approx\exp(-P/2)$, or $<10^{-100}$ for 4U 1145−619 and 10^{-8} for 1A 1118−615. To determine the centroid frequency, we used the Z^2 analysis (Buccheri et al. 1983) for the primary only (using no harmonics, justified by the nearly sinusoidal profiles; § 2.1.1). The frequencies and their uncertainties are listed in Table 1.

2.1.1. *Pulse Profiles*

In Figure 1 (*top*), we show the pulse profile of 4U 1145−619 in the 0.3–10 keV passband. The pulse profile is quasi-sinusoidal. While there appears to be a significant evolution in the spectral hardness (0.3–2.2 keV/2.2–10 keV) in phase (not pictured), with the hardest emission being observed when the intensity is highest, we are unable to determine how much of this is due to spectral evolution versus instrumental pileup effects.

We show the pulse profile for 1A 1118−615 in Figure 1 (*bottom*), showing significant intensity variability at the pulse frequency. We do not, however, detect significant variability in the hardness ratio; a χ^2 test comparing the data with the average value gives $\chi^2_\nu = 0.6$, 9 dof. A Spearman nonparametric rank correlation test (Press et al. 1995) gives only marginal evidence that the 0.3–2.2 keV count rate is correlated with the 2.2–10 keV count rate (probability that the two are uncorrelated is 0.02).

2.1.2. *Broadband Noise*

We rebinned the PDS logarithmically, after removing the frequency bin containing the pulsation centroid. The uncertainty in the power was taken to be the power itself, and summed as Gaussian random errors (van der Klis 1989). The PDS exhibited significant power at low frequencies in both 4U 1145−619 and 1A 1118−615. Modeling the PDS as a power law (with slope $\alpha_{\rm LFN}$) plus a Poisson level

$$P(\nu) = A_0 + A\nu^{-\alpha_{\rm LFN}}. \quad (1)$$

The Poisson level was observed to be suppressed from the theoretical value (2.0), which we attribute to dead time. In a linear dead time effect, all the PDS power can be approximately corrected to the levels they would exhibit in the absence of dead time by a factor $2.0/A_0$. Thus, the rms values we obtain are corrected by a dead time correction factor ${\rm DCF} = (2.0/A_0)^{1/2}$.

For 4U 1145−619, the best-fit rms variability was 17% ± 3%. Due to the fewer counts in the 1A 1118−615 data, a best-fit power-law slope was not found; we held the value fixed at $\alpha_{\rm LFN} = 0.5$ (similar to that found in 4U 1145−619), finding an rms fractional amplitude of 20^{+4}_{-6}%.

2.1.3. *Broadband Noise and the Pulsations*

The PDS of the two pulsars both exhibit broadband noise at low frequencies, which we attribute to active accretion. If the pulsed component is also powered by accretion, the pulsed intensity should be proportional to the instantaneous accretion-related intensity,

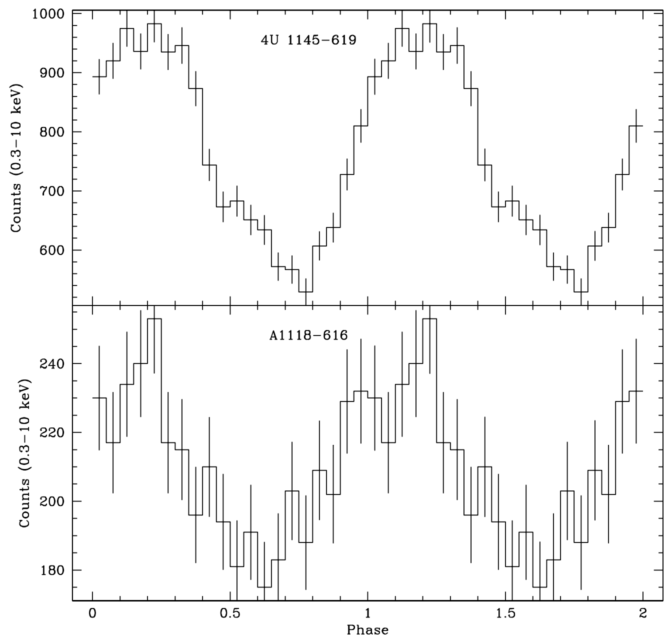

FIG. 1.—Folded light curves of 4U 1145−619 (*top*) and 1A 1118−615 (*bottom*), on their best-fit pulsation periods, using all detected counts. Two complete periods are shown.

$$I(t) = I_{\rm accretion}(t)\left[1 + r\cos(2\pi t/P_{\rm pulse})\right], \quad (2)$$

where r is the fractional amplitude, and $I_{\rm accretion}$ is the quasi-stochastic variable intensity. The FT convolution theorem states that the FT of the product of two functions is equal to the convolution of the FT of the individual functions (e.g., Press et al., 1995). We use the FT $F(\nu)$ of the observed signal $I(t)$ as a filter $A(\nu)$:

$$\begin{aligned} A(\nu) &= F(\nu) \qquad (0\ {\rm Hz} < \nu < \nu_p) \\ A(-\nu) &= -F(\nu) \qquad (0\ {\rm Hz} < \nu < \nu_p) \\ A(\nu = 0) &= 0 \qquad (\nu = 0), \end{aligned} \quad (3)$$

and $A(\nu) = 0$ elsewhere, where ν_p is the pulsation frequency. We use a filter width narrower than set by the pulsation frequency, as intensity variability on timescales shorter than the pulse period would have no effect on the pulsed intensity.

We convolve the FT $F(\nu)$ with this filter,

$$S(\nu) = \sum_{\nu'=-\nu_p\ {\rm Hz}}^{\nu'=\nu_p\ {\rm Hz}} F(\nu+\nu')A(\nu'). \quad (4)$$

To determine if $S(\nu_p)$ is significantly greater than random, we produce 10^4 Monte Carlo (MC) realizations of $S(\nu)$, where we randomize $F(\nu)$ in phase. If the measured $S(\nu_p)$ value is greater than 99.9% of the MC realizations, we would regard this as a detection of correlation between pulsed amplitude and the nonpulsed variability on timescales longer than the pulse period with 99.9% confidence.

In comparing $S(\nu_p)$ with the MC realizations for 4U 1145−619, we find that the value is greater than only ~35% of the MC realizations, a nondetection. However, further analysis, as we describe presently, demonstrates that this nondetection is due to a lack of sensitivity to this effect in the observation of 4U 1145−619.

Detection sensitivity of this analysis is related to the rms variability of the pulsed signal, the rms variability of the broadband noise, the source intensity, the form of the broadband noise, and the frequency width of the convolution filter. With regards to the last two, we simulated signals in which the broadband noise varied in its assumed power-law slope ($\alpha_{\rm LFN} = 2$, 1, 0.6, 0.3), and we permitted the filter width to range from the frequency resolution (that is, 1 frequency bin) to ν_p (77 frequency bins at the observation's frequency resolution). Assuming the same pulsed rms variability, broadband noise rms variability and source count rate as observed from 4U 1145−619, we found that for $\alpha_{\rm LFN} = 2.0$, the signal would be detected with 99.9% confidence for filter (half) widths >12 frequency bins. However, for flatter broadband noise ($\alpha_{\rm LFN} = 1$, 0.6, or 0.3), the detection significance was always below 99% confidence, independent of filter width. This makes intuitive sense: holding source flux constant, the greater the fraction of broadband variability that takes place on timescales comparable to the pulse period, the less sensitive will be the analysis for detecting correlation between pulsed amplitude and the nonpulsed intensity variability.

We interpret the results of this simulation as meaning, for 4U 1145−619 (for which we measure $\alpha_{\rm LFN} = 0.6$), that these observations are not sensitive to a correlation between the pulsed amplitude and source intensity. Likewise, for 1A 1118−615, with a lower pulsed rms variability, lower broadband noise rms variability, and lower observational signal-to-noise ratio, we presume that the observation is also not sensitive to such a correlation.

Thus, we are unable to conclusively demonstrate that the pulsed amplitude is correlated with the instantaneous source intensity in these observations.

2.2. *Spectroscopy*

We produced a phase-averaged spectrum for each source, fitting data between 0.5 and 10 keV, binned to energy bin widths at the energy resolution, or with 30 counts per bin, whichever produced a wider energy bin. We fit the phase-average spectra implementing a standard pileup model (Davis 2001), using an absorbed power law; the resulting spectral parameters are in Table 1.

For 4U 1145−619, the average counts per frame is 2.2; the source is off-axis by $4'$, which increases the area for the point-spread function (PSF) by a factor of ≈4. If we assume this decreases the equivalent count rate per frame per PSF by a factor of 4 (to 0.55 counts per frame per PSF), this corresponds to a pileup fraction of ≈20%,[7] and based the observed pulse fraction, we estimate that at no time during the observation did the pileup fraction exceed ∼50%, with a correspondingly large systematic effect on the estimated flux. However, the best-fit value of $\alpha_{\rm pileup}$ for the pileup model was at its maximum value ($\alpha_{\rm pileup} = 1$), confirming that the amount of pileup is at its extreme highest value for the Davis model. The X-ray spectral results therefore should be taken as an upper limit on spectral hardness, and the implied X-ray flux should be taken as a lower limit. For 1A 1118−615, we estimate the pileup fraction to be ≲3%, consistent with the results of the Davis pileup model ($\alpha_{\rm pileup} < 0.05$).

We do not report phase-resolved spectroscopy for either source. In the case of 4U 1145−619, the high pileup fraction makes it unclear that the Davis pileup correction is valid in this range. For 1A 1118−615, we see no evidence of phase-dependent spectral evolution in the broadband hardness ratio, which would warrant phase-resolved spectroscopy.

[7] Chandra Proposer's Observatory Guide Rev. 3.0, 2000 December; Figure 6.25.

3. DISCUSSION

We have detected pulsations from two transiently accreting X-ray pulsars, but at lower luminosities than these have previously been detected. Here, we consider possible mechanisms that might power their pulsed emission.

In the model for deep crustal heating (DCH; Brown et al. 1998) the minimum luminosity to be observed from a transiently accreting neutron star is provided from the core, heated by reactions in the NS crust during outburst, in proportion to the total mass accreted. The quiescent flux is predicted as a function of the time-average accretion flux,

$$L_q \approx 6 \times 10^{32}\ \text{ergs s}^{-1}(\langle \dot{M} \rangle / 10^{-11}\ M_\odot\ \text{yr}^{-1}), \qquad (5)$$

which gives a relation for the quiescent flux of $F_q \approx \langle F \rangle/200$, where $\langle F \rangle$ is the time-averaged flux from accretion outbursts.

We compiled the accretion outburst history for 4U 1145−619 and 1A 1118−615, based on 7 yr of BATSE monitoring (M. Finger 2002, private communication). Based on the $\langle F \rangle$, we predicted quiescent fluxes of 2.3×10^{-13} and 2.0×10^{-13} ergs cm^{-2} s^{-1} for 4U 1145−619 and 1A 1118−615, respectively. These DCH fluxes are a factor of 1100 and 30 below the fluxes we observe in these observations. Thus, DCH emission does not dominate the X-ray luminosity during these observations. The DCH flux for 4U 1145−619 is also below that observed previously (Mereghetti et al. 1987). This is consistent with the conclusion, based on the detection of broadband variability, that active accretion dominates the X-ray luminosity during these observations.

3.1. *Torques at $L_{\rm X} \sim 10^{34}$ ergs s^{-1} in 4U 1145−619*

For both systems, the measured pulse frequencies are lower than measured previously during outbursts (Bildsten et al. 1997). As we do not directly observe spin-down, we cannot provide definitive conclusions regarding the spin-down process. However, we will discuss spin-down for 4U 1145−619, assuming spin-down took place in less than the binary orbital period at the luminosity observed here.

If accreting matter interacts with the magnetosphere, it has been predicted to produce X-rays powered by gravitational potential energy, and to provide a torque on the magnetosphere as matter leaves the system with a velocity of r_m/P (Stella et al. 1986). We can compare the model predictions with our observed values, to explore the model implications relevant to these observations.

The observed X-ray luminosity would require a mass-accretion rate (assuming $r_m > r_{\rm co}$)

$$\frac{\dot{M}}{\dot{M}_{\rm Edd}} > 0.26\left[({\rm BC}) \times L_{\rm X,34}\right] P_2^{2/3} \qquad (6)$$

in units of the Eddington mass accretion rate ($\dot{M}_{\rm Edd}$), where (BC) is a bolometric correction, P_2 is the pulsar period in units of 10^2 s, and $L_{\rm X,34}$ is the measured 0.5–10 keV X-ray luminosity in units of 10^{34} ergs s^{-1}. This works out to be a super-Eddington mass accretion rate for 4U 1145−619. Since systematic monotonic spin-up is observed during presumably sub-Eddington X-ray outbursts in 4U 1145−619, and spin-down can occur only with $\dot{M}$ below the value at which spin-up occurs, then spin-down at the present luminosity requires rejecting the hypothesis that the observed

X-ray emission is produced by a shock at the magnetosphere under the prescription of Stella et al. (1986).

Assuming then that the observed X-ray luminosity results from accretion onto the NS surface, the mass accretion rate at the surface is $\dot{M}_{\rm surface} = 1.8 \times 10^{14}(\epsilon/0.2)({\rm BC})$ g s^{-1}, where $L_{\rm X} = \epsilon \dot{M}_{\rm surface} c^2/({\rm BC})$.

In 4U 1145−619, BATSE observed monotonic pulsar spin-up during outbursts from as low as $\nu = 3.4010(5)$ mHz to as high as $\nu = 3.4115(5)$ mHz, returning to a lower pulse frequency in quiescence (when the pulses were undetected with BATSE; Bildsten et al. 1997). The pulse frequencies observed during outburst are significantly above the $\nu = 3.397(1)$ mHz frequency we observe. This implies that 4U 1145−619 spins down during quiescence by $\Delta\nu > (4 \pm 1) \times 10^{-6}$ Hz, and possibly as great as $(15 \pm 1) \times 10^{-6}$ Hz over a timescale $\Delta T = 186.5$ days (the orbital period). If the implied torque is due to a mass outflow $\chi \dot{M}_{\rm surface}$, where χ is a multiplicative factor, from a radius $r_m \geq r_{\rm co}$, carrying away angular momentum equal to that of matter in Keplerian orbit at the same radius, then

$$I \frac{2\pi\Delta\nu}{\Delta T} = \chi \dot{M}_{\rm surface} \sqrt{G M_{\rm NS} r_{\rm co}} \left(\frac{r_m}{r_{\rm co}}\right)^{1/2}, \quad (7)$$

which solving for χ

$$\chi = 6 I_{45} \left(\frac{\Delta\nu}{10^{-6}\ {\rm Hz}}\right) \left(\frac{186\ {\rm days}}{\Delta T}\right) \left(\frac{r_{\rm co}}{r_m}\right)^{1/2} \frac{(\epsilon/0.2)}{({\rm BC}) L_{\rm X,34}}, \quad (8)$$

where I_{45} is the moment of inertia in units of 10^{45} g cm^2 and $L_{\rm X,34}$ is the observed X-ray luminosity in units of 10^{34} ergs s^{-1}. For 4U 1145−619 to produce the observed spin-down by mass removing angular momentum from r_m, a factor of $\sim$6 greater mass leaves the system than is accreted to the NS surface.

In conclusion, the Stella model would require a mass accretion rate greater than observed during even much higher X-ray luminosity outbursts, which seems physically implausible, and we therefore do not favor that model to explain these observations.

Alternatively, if the observed change in frequency were due exclusively to a Doppler shift caused by orbital motion, the implied difference in velocity ($\Delta V \geq 350 \pm 88$ km s^{-1}) is greater than the circular velocity of a neutron star around a 10 $M_\odot$ primary in a 187 day period ($\approx$80 km s^{-1}). The rms (time averaged) velocity decreases from $\approx$57 km s^{-1} (at eccentricity $e = 0$) as e increases, so it is unlikely that the observed difference in pulsation frequency is due exclusively to orbital motion, although the possibility cannot be excluded with the present data.

Menou et al. (1999) calculated the fraction of mass reaching the NS surface (f) from a quasi-spherical accretion flow to be $f \approx 3/8 [P_{\rm pulse}/P_{\rm K}(r_m)]^4$, where $P_{\rm K}(r_m)$ is the Keplerian period at the magnetosphere (a related calculation is performed by Campana et al. 2001). To obtain the order of the value found in eqaution (8) ($f = 1/\chi \sim 0.17$) would require the magnetospheric radius to be related to the corotation radius $r_m = (3\chi/8)^{1/6} r_{\rm co}$, roughly 14% larger for $\chi = 6$. However, this estimate is due only to geometry, and ignores the effect of the rotating magnetic field offset from the spin axis.

The issues we speculate on in this section could be further explored by observations. One could determine the companion's wind mass flux, and separate orbital Doppler-shift-related changes in the observed pulse period from those due to spin-down, by monitoring the pulse period variations over an orbital period. Using generalized assumptions about the strength of the magnetic dipole, this would permit measurement of the spin-down magnitude as a function of accretion rate at the magnetosphere. This could reveal much about magnetospheric interaction with an accreting wind.

4. CONCLUSIONS

We report the redetection and the third discovery of pulsations from transiently accreting X-ray pulsars at low luminosities ($\lesssim 10^{35}$ ergs s^{-1}), 4U 1145−619 and 1A 1118−615. We observe broadband intensity variability in both (0.00005–0.1 Hz; $\approx$17%–20% rms). Such strong intensity variability on short timescales cannot be produced via deep crustal heating (Brown et al. 1998; Ushomirsky & Rutledge 2001), and we conclude it is most likely due to accretion.

The present observations do not favor an interpretation of an X-ray shock at the magnetosphere of 4U 1145−619 as powering its X-ray luminosity during this observation. If future observations demonstrate spin-down at the present luminosities, this would rule out shock as powering the quiescent luminosity, and indicate that comparable amounts of matter accrete to the NS surface as escape the system from the magnetosphere due to the propeller effect. Such spin-down would also imply that the magnetosphere is larger than the corotation radius, requiring surface dipole magnetic field strengths $\gtrsim 10^{13}$ G.

The pulsation frequencies observed from these two sources are significantly below those observed during outburst monitoring with BATSE. The spin-down history prior to the present observations has not been observed, and so it is unclear if this is due to accretion-moderated spin-down, the orbital parameters of the NS, or some other mechanism. We considered the low pulsation frequencies as due to a torque applied due to mass outflow, and concluded that this requires, in the specific case of 4U 1145−619, $\approx 30\times$ as much mass leaving the system carrying angular momentum with it as accretes to the NS surface.

Future observations of these pulsars will permit determination of their orbital elements and spin-down properties, as well as provide a laboratory for studying interaction between the NS magnetic field and mass flow across it (Arons & Lea 1976; Toropina et al. 2001).

We are indebted to the anonymous referee for very useful comments. Support for this work was provided by NASA through Chandra Award Number GO3-4054A issued by the *Chandra* X-Ray Observatory Center, which is operated by the SAO for and on behalf of NASA under contract NAS8-39073. We also thank the NSF for support under contract PHY 99-07949. The work of V. E. Zavlin is supported by a National Research Council Research Associateship Award at NASA/MSFC.

REFERENCES

Arons, J., & Lea, S. M. 1976, ApJ, 207, 914
Bildsten, L., et al. 1997, ApJS, 113, 367
Bradt, H. V., et al. 1977, Nature, 269, 21
Brown, E. F., Bildsten, L., & Rutledge, R. E. 1998, ApJ, 504, L95 (BBR98)
Buccheri, R., et al. 1983, A&A, 128, 245
Campana, S., Gastaldello, F., Stella, L., Israel, G. L., Colpi, M., Pizzolato, F., Orlandini, M., & Dal Fiume, D. 2001, ApJ, 561, 924
Campana, S., Stella, L., Israel, G. L., Moretti, A., Parmar, A. N., & Orlandini, M. 2002, ApJ, 580, 389
Chevalier, C., & Ilovaisky, S. A. 1998, A&A, 330, 201

Cook, M. C., & Warwick, R. S. 1987, MNRAS, 225, 369
Davidson, K., & Ostriker, J. P. 1973, ApJ, 179, 585
Davis, J. E. 2001, ApJ, 562, 575
Dower, R. G., Bradt, H. V., Doxsey, R. E., Jernigan, J. G., Kulik, J., & Apparao, K. M. V. 1978, Nature, 273, 364
Frigo, M., & Johnson, S. G. 1998, Proc. 1998 ICASSP Conf., 3, 1381
Garmire, G. P., Bautz, M. W., Ford, P. G., Nousek, J. A., & Ricker, G. R. 2003, SPIE Proc., 4851, 28
Heindl, W. A., Rothschild, R. E., Coburn, W., Staubert, R., Wilms, J., Kreykenbohm, I., & Kretschmar, P. 2004, in AIP Conf. Proc. 714, X-Ray Timing 2003: Rossi and Beyond, ed. P. Kaaret, F. K. Lamb, & J. H. Swank (New York: AIP), 323
Illarionov, A. F., & Sunyaev, R. A. 1975, A&A, 39, 185
Inoue, H., et al. 2005, Astron. Tel., 613, 1
Janot-Pacheco, E., Ilovaisky, S. A., & Chevalier, C. 1981, A&A, 99, 274
Kretschmar, P., et al. 2005, Astron. Tel., 601, 1
Leahy, D. A., Darbro, W., Elsner, R. F., Weisskopf, M. C., Kahn, S., Sutherland, P. G., & Grindlay, J. E. 1983, ApJ, 266, 160
Levine, A. M., Bradt, H., Cui, W., Jernigan, J. G., Morgan, E. H., Remillard, R., Shirey, R. E., & Smith, D. A. 1996, ApJ, 469, L33
Menou, K., Esin, A. A., Narayan, R., Garcia, M. R., Lasota, J. P., & McClintock, J. E. 1999, ApJ, 520, 276
Mereghetti, S., Bignami, G. F., Caraveo, P. A., & Goldwurm, A. 1987, ApJ, 312, 755
Motch, C., Pakull, M. W., Janot-Pacheco, E., & Mouchet, M. 1988, A&A, 201, 63
Negueruela, I., Reig, P., Finger, M. H., & Roche, P. 2000, A&A, 356, 1003
Polcaro, V. F., Villada, M., & Giovannelli, F. 1993, A&A, 273, L49
Press, W., Flannery, B., Teukolsky, S., & Vetterling, W. 1995, Numerical Recipes in C (2nd ed.; Cambridge: Cambridge Univ. Press)
Priedhorsky, W. C., & Terrell, J. 1983, ApJ, 273, 709
Roberts, M. S. E., Michelson, P. F., Leahy, D. A., Hall, T. A., Finley, J. P., Cominsky, L. R., & Srinivasan, R. 2001, ApJ, 555, 967
Schulz, N., Kahabka, P., & Zinnecker, H. 1995, A&A, 295, 413
Stella, L., White, N. E., & Rosner, R. 1986, ApJ, 308, 669
Stevens, J. B., Reig, P., Coe, M. J., Buckley, D. A. H., Fabregat, J., & Steele, I. A. 1997, MNRAS, 288, 988
Toropina, O. D., Romanova, M. M., Toropin, Y. M., & Lovelace, R. V. E. 2001, ApJ, 561, 964
Ushomirsky, G., & Rutledge, R. E. 2001, MNRAS, 325, 1157
van der Klis, M. 1989, in Timing Neutron Stars, ed. H. Ögelman & E. P. J. van den Heuvel (Dordrecht: Kluwer), 27
Villada, M., Rossi, C., Polcaro, V. F., & Giovannelli, F. 1999, A&A, 344, 277
Watson, M. G., Warwick, R. S., & Ricketts, M. J. 1981, MNRAS, 195, 197
Wilson, C. A., & Finger, M. H. 2005, Astron. Tel., 605, 1