SLAC-PUB-8483
June 2000
NRL-JA-7620-2000-62
Astro-ph/0006234

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Submitted to Astrophysical Journal Letters

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported by Department of Energy contract DE–AC03–76SF00515.

Submitted to *ApJ Letters*, 2000 June 16
Preprint typeset using LaTeX style emulateapj v. 04/03/99

arXiv:astro-ph/0006234 16 Jun 2000

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ABSTRACT

The USA experiment on *ARGOS* and *RXTE* have exensively observed the X-ray transient XTE J1118+480 during its recent outburst in 2000 April–June. We present detailed monitoring of the evolution of a low frequency QPO which drifts from 0.07 Hz to 0.15 Hz during the outburst. We examine possible correlations of the QPO frequency with the flux and spectral characteristics of the source, and compare this QPO to low frequency QPOs observed in other black hole candidates.

Subject headings: stars: individual (XTE J1118+480) — stars: binaries — X-rays: binaries

1. BACKGROUND ON XTE J1118+480

The transient source XTE J1118+480 (Remillard et al. 2000) in Ursa Major appeared as an X-ray source in the first few days of 2000 and has continued to be detectable through the subsequent six months. Its X-ray activity to date has consisted of two distinct outbursts, the first of which rose to maximum rapidly and declined in 2000 January. The rise to the second maximum followed about 25 days after the decline from the first and it was during this second maximum that the All Sky Monitor (ASM) on the *Rossi X-ray Timing Explorer* (*RXTE*) discovered the source. The discovery announcement noted the earlier maximum based on pre-discovery observations.

XTE J1118+480 is tentatively classified as a black hole transient based on the detection of low-frequency quasi-periodic oscillations (QPOs), lack of high-frequency noise (Revnivtsev, Sunyaev, & Borozdin 2000), and power-law photon spectrum extending to at least 120 keV (Wilson & McCollough 2000). However, no dynamical mass measurement has yet been made for the compact object, preventing definitive identification as a black hole. The X-ray flux is low, not having exceeded 75 mCrab at any time to date. Tentative distance estimates to the putative optical counterpart based on companion spectral types in other X-ray transients (Uemura et al. 2000) imply an unusually low X-ray luminosity ($L_X \sim 10^{34} - 10^{35}$ erg/s). Its Galactic latitude of 62° is extremely high for this source class, and the nominal distance would place it in the Galactic halo (Uemura et al. 2000). The second outburst has prompted extensive multi-wavelength monitoring, including observations in radio, optical, EUV, soft X-rays and hard X-rays. A continuous spectrum is inferred from optical to hard X-rays with the photon spectral index determined in X-rays as 1.8 ± 0.1 (Hynes et al. 2000).

X-ray variability of the source is characterized in the time domain by repeated flaring on timescales of a few seconds. The power spectrum shows a variable, low-frequency QPO near 0.1 Hz, first reported from observations with the Proportional Counter Array (PCA) on *RXTE* (Revnivtsev, Sunyaev, & Borozdin 2000). An outstanding feature of the source is that the QPO is seen in X-rays, EUV and optical (Haswell et al. 2000). The optical source shows a photometric period, presumably orbital, of 4.1 hours (Uemura et al. 2000). During the outburst the source has brightened from $V \gtrsim 18.8$ in quiescence to $V \approx 13$ (Uemura et al. 2000).

This *Letter* reports X-ray observations made with the Unconventional Stellar Aspect (USA) experiment on the US Air Force *Advanced Research and Global Observation Satellite* (*ARGOS*) and the PCA on *RXTE*. The ~ 0.1Hz QPO is detected in most USA and *RXTE* observations, providing a picture of the evolution of this QPO over more than 60 days with unprecedented coverage. The USA observing sequence was initiated as soon as possible after the first report (Remillard et al. 2000) of the transient and has subsequently been maintained through the remainder of the second maximum of the outburst. The high revisit frequency of USA observations is meant to provide, among other things, a framework for linking up and correlating multi-wavelength observations.

2. DESCRIPTION OF THE USA EXPERIMENT

USA is an X-ray timing experiment built jointly by the Naval Research Laboratory and the Stanford Linear Accel-

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erator Center for the dual purposes of conducting studies of variability in X-ray sources and exploring applications of X-ray sensor technology (see Ray *et al.* 1999 for a more detailed description). USA was launched on 1999 February 23 on *ARGOS* into a nearly circular 830 km orbit at 98.8°inclination. It is a reflight of two proportional counter X-ray detectors flown previously on the NASA *Spartan-1* mission (Kowalski et al. 1993), after which they were recovered and refurbished. The primary observing targets are bright Galactic X-ray binaries, with a goal of obtaining large exposures on a modest number of sources.

The detector consists of two multiwire constant-flow proportional counters equipped with a 5.0 μm Mylar window and an additional 1.83 μm thick aluminized Mylar heat shield. The detector gas is a mixture of 90% argon and 10% methane (P-10) at a pressure of 16.1 psia (at room temperature). The detectors are sensitive in the range 1–15 keV with an effective area of about 1000 cm^2 per detector at 3 keV. The collimators serve to support the window as well as to define the field of view, which is approximately 1.2° FWHM circular. The Crab Nebula gives about 4000 cts/s in one detector at the center of the field of view. The *ARGOS* spacecraft on which USA is mounted is three-axis-stabilized and nadir-pointed. Consequently, the X-ray detectors are mounted on a 2-axis gimballed platform to permit inertial pointing at celestial objects. The pitch and yaw drive capability is $\sim 3.5°$/min (track) and ~ 20 °/min (slew) and the common pitch/yaw pivot design allows 180° travel in each axis.

USA has five telemetry modes, four event and one spectral. Events are time-tagged to an onboard GPS receiver which provides an absolute time reference. Events are recorded with either 32 μs time resolution and 16 pulse height channels or 2 μs resolution with 8 channels. Event modes can be used up to count rates of ~1000 cts/s at 40 kbps or ~6000 cts/s at 128 kbps before events are discarded. Spectral mode records a 48 channel spectrum every 10 ms.

The USA instrument has performed well since activation began on 1999 April 30, but the mission has not been without difficulties. Approximately two weeks after launch the detector heat shields suffered from degradation which has imposed additional constraints on USA pointing with respect to the Sun. On 1999 June 8, Detector 2 developed a rapid gas leak, possibly caused by a micrometeor impact, and exhausted its gas supply leaving only Detector 1 to complete the mission, halving the effective area.

3. OBSERVATIONS AND DATA ANALYSIS

USA has obtained a total of 425 ks of data on XTE J1118+480 between 2000 April 10 and June 13. These observations are continuing through the duration of the outburst. Using the 32 μs event mode, the source was observed between 5 and 11 times per day, providing the most consistent sampling of its X-ray behavior in existence. We have also utilized the 24 public target-of-opportunity (TOO) observations of XTE J1118+480 made by *RXTE* between 2000 April 13 and June 11. Analysis of the USA and *RXTE* data, including energy selection, binning, construction of the power spectra, and energy spectral fitting, was performed using FTOOLS v5.0.1. Typically the observed QPO has a fractional RMS amplitude of ~ 5% and a FWHM of ~0.01 Hz. Additionally, in some cases there are suggestions of multiple peaks in the power spectra. Detailed results of our QPO analysis are summarized in Table 1.

3.1. *USA*

To search for QPOs in the USA data, we created 30 groups of observations, each of which contain 4–8 individual observations from within a continuous interval of 8–20 hours. Due to the nearly polar orbit of USA, the usable time from each individual observation varies in length between 300 and 1100 seconds; hence the total on-source integration time contained in each group ranges from 1.8 to 4.9 ks. To construct the power spectrum for each group of USA observations, we selected channels 1–8, corresponding to an energy range of 1–10 keV, and binned the data by either 0.1 or 0.125 seconds. Power spectra of length 4096 were computed and averaged for each observation, the expected Poisson level subtracted, and normalized to fractional RMS^2/Hz (see Nowak *et al.* 1999 and references therein for a detailed description of power spectral analysis of X-ray data). The QPO parameters were determined by fitting the resultant power spectra between 0.03 and 0.8 Hz to a power law plus a Gaussian QPO feature. The centroid and FWHM of the feature were determined from the fit parameters and the fractional RMS attributed to the QPO was determined from the integral of the Gaussian profile. USA average fluxes for each observation are determined by subtracting a background model and correcting for obscuration of the detector by the instrument support structure.

3.2. *RXTE*

The power spectra from the *RXTE* observations were generated from the `Standard1` data which bin all of the good counts in each detector at 0.125 s (Jahoda et al. 1996). These time series were summed for all active PCUs and the power spectra were computed and fitted as described above for the USA data. Spectral fits were also made using the PCA data, employing the background models and response matrices provided by the *RXTE* team. We fit a pure power law model between 2.5 and 20 keV to each of the RXTE observations listed in Table 1. This provided a reasonably good fit to the data, but the residuals typically show excesses below 4 keV and near 6 keV. We find that the photon spectral index is consistent with a constant at 1.79±0.01 before MJD 51683 and then appears to soften to 1.83±0.01. This softening appears to correspond to an increase in the residuals below 4 keV, suggesting that it may be caused by the appearance of a soft component in the spectrum. The excess is not well determined because most of the flux falls below the low-energy cutoff of the PCA, but it can be fitted with a 0.25 keV blackbody spectrum.

4. DISCUSSION

4.1. *Source Models*

Examining the options for the nature of this unusual X-ray transient, we note that its emission characteristics and timescales require a compact stellar object, but the hard X-ray spectrum excludes a white dwarf. A neutron star model has not been supported by detection of signatures such as pulsations, Type I X-ray bursts, or high frequency

QPO activity. There may be a marginal advantage for a neutron star in accounting for the low luminosity, but not the spectral and temporal properties. Therefore the observed X-ray characteristics of XTE J1118+480 seem to be best explained by identification of this source as a binary black hole transient in the canonical low hard state. However, this source is far from a typical example of that class. The low luminosity is exceptional, and it is also highly unusual for a black hole transient to make its first appearance in the low hard state. (In this regard Uemura *et al.* (2000) have suggested that the source is viewed at high inclination, but there are no observed eclipses to support this suggestion.) The Galactic halo location of XTE J1118+480 and the X-ray/EUV/optical QPO are unique, although previous transients of this type have shown X-ray and optical correlated variability. The ratio of the X-ray to optical flux is also extremely low, leading to speculation that this outburst of XTE J1118+480 may be a "mini-outburst" of the type seen in the black hole candidate system GRO J0422+32 (Hynes et al. 2000). We also note that short-timescale X-ray and optical variability similar to that seen in XTE J1118+480 has been observed in the hard state of the black hole candidate GX 339−4 (Motch et al. 1983). Merloni *et al.* (2000) suggest that both the optical and hard X-ray flaring in XTE J1118+480 are due to magnetic flares in a Comptonizing corona and predict X-ray/optical correlations which can be tested with ongoing multi-wavelength observations.

4.2. *QPO Evolution*

Figure 1 shows the evolution of the source flux as monitored by the ASM on *RXTE* (Levine et al. 1996) and the QPO centroid as measured by USA and *RXTE*. The QPO moves upward in frequency over the 62 days of observations, apparently monotonically, but with significant changes in rate. During the same period, the 2–12 keV X-ray flux slowly rises, then begins to decrease. Figure 2 shows the QPO centroid frequency versus measured USA (1–10 keV) fluxes. Clearly, the QPO frequency fails to track the source intensity according to a simple proportionality.

This effect could be correlated with change in the source energy spectrum. However, the power-law component seen with the PCA stays essentially constant while the QPO frequency changes by a factor of two. It is possible that the soft ($\sim$ 0.25 keV) component tracks the state of the accretion disk and thus the QPO frequency. The variable flux in the power-law component would then be due to inverse-Compton scattered seed photons from the variable disk component.

Low-frequency QPOs have been seen in several black hole binaries in the low hard state, including Cyg X-1, GRO J0422+32, and GX339−4. Unlike the QPO observed in XTE J1118+480 , the $\sim$0.3 Hz QPO observed in the low hard state of GX339−4 appears to be relatively stable, but like XTE J1118+480 no simple correlation between the QPO frequency and source flux was found (Nowak, Wilms, & Dove 1999). Variable low-frequency QPOs have been observed during the high and intermediate states of the black hole transient XTE J1550−564. In this source, the QPO frequency generally increases as the disk flux increases (Sobczak et al. 1999). However, we note that the time evolution of the variable QPO in XTE J1550−564 is more erratic than in XTE J1118+480 with the QPO frequency increasing and decreasing multiple times within a similar interval ($\sim$60 days).

5. SUMMARY

The QPO in XTE J1118+480 shows an upward drift from 0.07 Hz to 0.15 Hz over a 62 day time interval while the source intensity slowly rises and then decreases. The effect is clear but the explanation seems to call for changes in the disk state that are not completely specified by measurement of the 2–12 keV X-ray spectrum, possibly by a variable soft disk component which is not well determined by our observations. We are further investigating the variability by studying flaring in the time domain. The flare events, which have a large signal-to-noise ratio and occur on the same timescale as the QPO, may shed light on the physical processes behind the QPO. Continued X-ray observations will be important for covering a larger dynamic range in the flux and continuing to track the QPO centroid.

Basic research in X-ray Astronomy at the Naval Research Laboratory is supported by the Office of Naval Research. Work at SLAC was supported by Department of Energy contract DE-AC03-76SF00515. This paper made use of quick-look results provided by the ASM/*RXTE* team (see `http://xte.mit.edu`).

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Table 1
Parameters of low-frequency QPO in XTE J1118+480

UT Start	UT End	T_{obs} (ks)	Frequency (Hz)	FWHM (Hz)	rms (%)	Count rate[a] (counts s^{-1})	Instrument
10 Apr 18:27	11 Apr 06:31	4.1	0.0689±0.0011	0.0115±0.0022	6.7±1.6	107.5	USA
11 Apr 18:10	12 Apr 06:14	4.9	0.0716±0.0013	0.0138±0.0025	6.2±1.5	100.8	USA
12 Apr 19:34	13 Apr 05:56	4.2	0.0724±0.0007	0.0064±0.0012	5.9±1.8	102.5	USA
13 Apr 09:44	13 Apr 14:02	11.2	0.0769±0.0006	0.0109±0.0013	6.9±1.1	410.4	XTE(3)
13 Apr 14:25	13 Apr 15:40	3.1	0.0774±0.0012	0.0098±0.0022	6.5±2.1	406.1	XTE(3)
13 Apr 20:59	14 Apr 07:22	3.0	0.0790±0.0008	0.0058±0.0016	5.5±2.1	103.1	USA
14 Apr 14:02	15 Apr 00:20	4.4	0.0818±0.0018	0.0094±0.0032	4.4±1.7	103.0	USA
15 Apr 07:59	15 Apr 08:20	1.1	0.0818±0.0013	0.0125±0.0026	9.6±3.7	689.8	XTE(5)
17 Apr 05:10	17 Apr 07:12	4.1	0.0838±0.0026	0.0318±0.0058	8.2±1.8	419.5	XTE(4)
18 Apr 17:50	19 Apr 05:52	5.0	0.0884±0.0008	0.0106±0.0018	5.6±1.4	97.4	USA
18 Apr 21:47	18 Apr 23:02	1.8	0.0861±0.0017	0.0146±0.0037	7.7±2.7	455.8	XTE(3)
20 Apr 14:01	21 Apr 00:18	4.5	0.0827±0.0014	0.0158±0.0031	5.7±1.4	96.4	USA
21 Apr 04:17	21 Apr 04:34	0.9	0.0873±0.0010	0.0060±0.0017	7.8±3.8	700.4	XTE(5)
21 Apr 20:21	22 Apr 06:44	3.9	0.0884±0.0008	0.0062±0.0013	5.1±1.7	93.3	USA
23 Apr 19:46	24 Apr 09:46	2.4	0.0885±0.0014	0.0095±0.0026	4.1±1.7	99.7	USA
25 Apr 14:12	26 Apr 00:32	3.5	0.0980±0.0008	0.0089±0.0008	5.3±1.2	92.5	USA
26 Apr 13:59	26 Apr 22:37	3.2	0.0930±0.0012	0.0149±0.0024	7.3±1.5	90.9	USA
27 Apr 13:35	28 Apr 06:41	4.3	0.0956±0.0017	0.0225±0.0034	7.9±1.6	89.0	USA
29 Apr 16:22	30 Apr 07:50	3.7	0.0955±0.0010	0.0089±0.0018	4.9±1.3	94.6	USA
30 Apr 17:45	1 May 07:32	4.0	0.1029±0.0008	0.0089±0.0008	5.5±1.6	88.4	USA
1 May 11:25	1 May 11:59	1.8	0.0994±0.0009	0.0097±0.0020	7.9±2.6	446.5	XTE(3)
1 May 15:47	1 May 22:51	3.3	0.0979±0.0010	0.0108±0.0020	5.8±1.5	84.3	USA
2 May 13:49	2 May 22:34	4.2	0.1010±0.0008	0.0080±0.0015	5.2±1.2	83.7	USA
3 May 18:35	4 May 08:22	4.2	0.0990±0.0007	0.0080±0.0013	5.5±1.5	86.8	USA
5 May 16:19	6 May 04:19	3.0	0.1068±0.0018	0.0213±0.0035	6.8±1.4	80.3	USA
6 May 12:47	6 May 19:46	3.4	0.1106±0.0020	0.0122±0.0035	4.3±1.7	79.3	USA
7 May 14:10	8 May 03:44	4.1	0.1135±0.0014	0.0140±0.0030	5.6±1.5	77.3	USA
9 May 05:04	9 May 20:35	2.4	0.1133±0.0013	0.0075±0.0024	4.8±2.0	77.2	USA
11 May 15:32	11 May 16:15	2.3	0.1127±0.0026	0.0241±0.0057	7.1±2.2	525.6	XTE(4)
11 May 17:08	11 May 18:04	2.8	0.1122±0.0010	0.0108±0.0019	6.4±1.5	529.2	XTE(4)
11 May 18:46	11 May 22:26	7.7	0.1184±0.0012	0.0187±0.0033	5.8±1.4	456.1	XTE(4)
16 May 19:54	17 May 04:30	2.5	0.1187±0.0011	0.0136±0.0029	6.6±1.8	72.7	USA
17 May 23:00	18 May 07:41	1.9	0.1140±0.0019	0.0109±0.0034	5.3±2.3	85.3	USA
20 May 05:15	20 May 20:45	3.4	0.1173±0.0012	0.0075±0.0023	3.7±1.5	72.9	USA
23 May 00:08	23 May 00:36	1.6	0.1188±0.0024	0.0148±0.0059	5.2±2.7	379.5	XTE(3)
25 May 17:17	26 May 00:18	3.2	0.1272±0.0006	0.0078±0.0013	4.6±1.2	75.9	USA
26 May 15:18	27 May 06:44	2.5	0.1240±0.0014	0.0183±0.0026	7.4±1.4	77.5	USA
27 May 08:19	27 May 08:51	1.7	0.1171±0.0055	0.0526±0.0128	9.5±2.9	509.0	XTE(4)
27 May 16:42	28 May 09:56	1.8	0.1273±0.0036	0.0247±0.0079	4.7±1.9	85.1	USA
1 Jun 03:27	1 Jun 23:57	2.6	0.1275±0.0013	0.0130±0.0025	5.8±1.5	79.7	USA
3 Jun 13:01	4 Jun 02:40	3.0	0.1247±0.0022	0.0278±0.0047	6.8±1.5	80.2	USA
4 Jun 12:44	5 Jun 05:47	2.2	0.1341±0.0012	0.0122±0.0027	4.9±1.6	80.8	USA
11 Jun 01:46	11 Jun 02:35	1.8	0.1591±0.0027	0.0244±0.0053	6.7±2.1	376.0	XTE(3)

[a]Average raw count rate, not background subtracted or otherwise corrected, as used in the QPO analysis (XTE points are Standard1 count rates for the number of detectors indicated in parentheses).

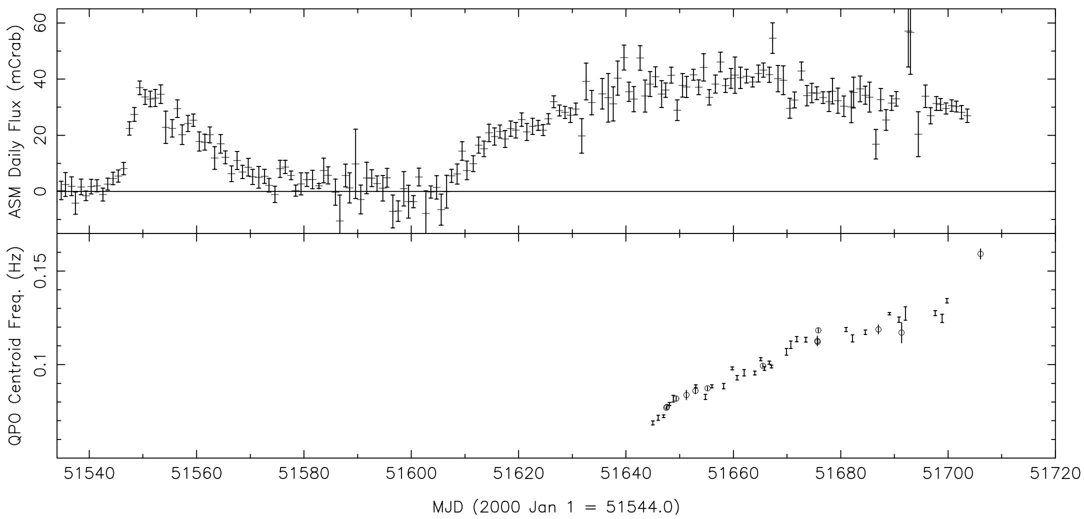

FIG. 1.— ASM daily average fluxes (top panel) and QPO centroid frequencies. In the lower panel, capped error bars are QPO measured with USA, while open circles represent QPO found in the *RXTE* PCA data.

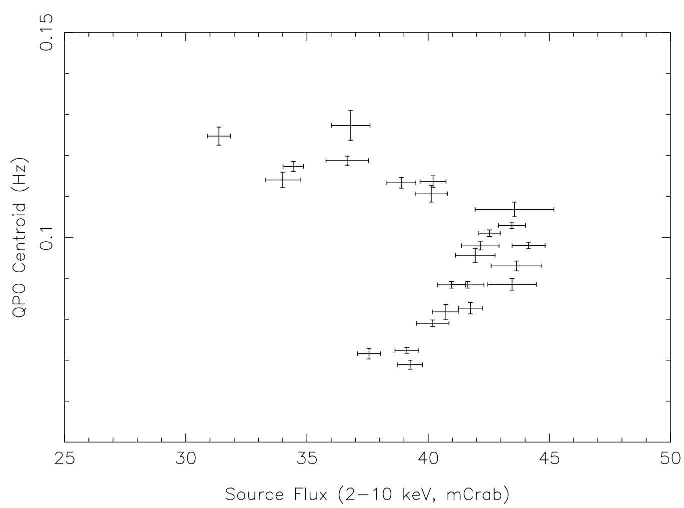

FIG. 2.— Measured QPO centroid frequency vs. source flux for each USA observation of XTE J1118+480. Source fluxes are in mCrab, having been background subtracted and corrected for obscuration of the detector by the support structure.