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EVIDENCE FROM QUASI-PERIODIC OSCILLATIONS FOR A MILLISECOND PULSAR IN THE LOW-MASS X-RAY BINARY 4U 0614+091

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ABSTRACT

We have detected quasi-periodic oscillations (QPOs) near 1 kHz from the low-mass X-ray binary 4U 0614+091 in observations with the *Rossi X-Ray Timing Explorer*. The observations span several months and sample the source over a large range of X-ray luminosity. In every interval, QPOs are present above 400 Hz with fractional rms amplitudes from 3% to 12% over the full Proportional Counter Array energy band. At high count rates, two high-frequency QPOs are detected simultaneously. The difference in their frequency centroids is consistent with a constant value of 323 ± 4 Hz in all observations. During one interval, a third signal is detected at 328 ± 2 Hz. This suggests that the system has a stable "clock" that is most likely the neutron star with spin period 3.1 ms. Thus, our observations of 4U 0614+091, and those of 4U 1728−34 and KS 1731−260, provide the first evidence for millisecond pulsars within low-mass X-ray binary systems and reveal the "missing-link" between millisecond radiopulsars and the late stages of binary evolution in low-mass X-ray binaries. The constant difference in the high-frequency QPOs suggests a beat-frequency interpretation. In this model, the high-frequency QPO is associated with the Keplerian frequency of the inner accretion disk, and the lower frequency QPO is a "beat" between the differential rotation frequency of the inner disk and the spinning neutron star. Assuming the high-frequency QPO is a Keplerian orbital frequency for the accretion disk, we find a maximum mass of 1.9 $M_\odot$ and a maximum radius of 17 km for the neutron star.

Subject headings: accretion, accretion disks — pulsars: general — stars: individual (4U 0614+091) — stars: neutron — X-rays: stars

1. INTRODUCTION

High-frequency quasi-periodic oscillations (QPOs) have now been discovered with the *Rossi X-Ray Timing Explorer* (*RXTE*) in several low-mass X-ray binaries (LMXBs) (e.g., van der Klis et al. 1996a; Strohmayer et al. 1996; Berger et al. 1996; Zhang et al. 1996). The fast variability of these signals is a direct result of the short dynamical timescale in the region near the compact object where the emission is produced. Study of these QPO phenomena addresses questions about the accretion flow around the central compact object and the nature of the compact object itself.

Here we present the discovery of high-frequency QPOs in 4U 0614+091 (Ford et al. 1996a). The X-ray source 4U 0614+091 has been identified as an X-ray burster (Swank et al. 1978; Brandt et al. 1992; Brandt 1994). It is a probable atoll source (Singh & Apparao 1995). The source 4U 0614+091 has been detected up to 100 keV with episodes of bright hard X-ray emission anticorrelated with the soft X-ray flux (Ford et al. 1996b).

The *RXTE* observations of 4U 0614+091 constitute one of the most extensive data sets to date of the new high-frequency QPO phenomenon. We have measured the QPOs over a wide range in frequency from 480 to 1150 Hz. Their behavior is relatively simple, being determined mainly by the source luminosity. The observations, analysis, and results are discussed in §§ 2 and 3. In § 4, we argue that 4U 0614+091 harbors a millisecond pulsar, a fact which has implications for pulsar evolution scenarios. We interpret the QPO production in terms of a simple model and use the QPO frequency to place limits on the mass and radius of the neutron star.

2. OBSERVATIONS AND ANALYSIS

We observed 4U 0614+091 with the *RXTE* (Bradt, Rothschild, & Swank 1993) for 10 ks starting UTC 1996 April 22 19:18:43, 33 ks beginning 1996 April 24 13:18:37, and 16 ks beginning 1996 August 6 20:05:00. The following results utilize Proportional Counter Array (PCA) (Zhang et al. 1993) data with 122 μs time resolution and good sensitivity from approximately 1 to 30 keV. The observations of 4U 0614+091 divide into intervals of continuous coverage, with typical durations of 3000 s separated by Earth occultations and/or South Atlantic Anomaly passages. No X-ray bursts are present in any of the observations.

Power spectra are generated from count rate data binned in 122 μs intervals in consecutive windows of 1 s duration, yielding a Nyquist cutoff frequency of 4096 Hz and a transform window function of approximately 1 Hz. The baseline power is approximately 0.3% below the expected value of 2.0 (Leahy et al. 1983) because of an instrumental dead time of approximately 10 μs. No additional cuts were made on the PCA energy channels.

In order to calculate count rates and rms fractions, we must correct for the time-varying background, which is 100–150 counts s^{-1} compared with a total source count rate of 400–700 counts s^{-1}. We first note that in Earth occultation, the background rejection channels returned as PCA data products

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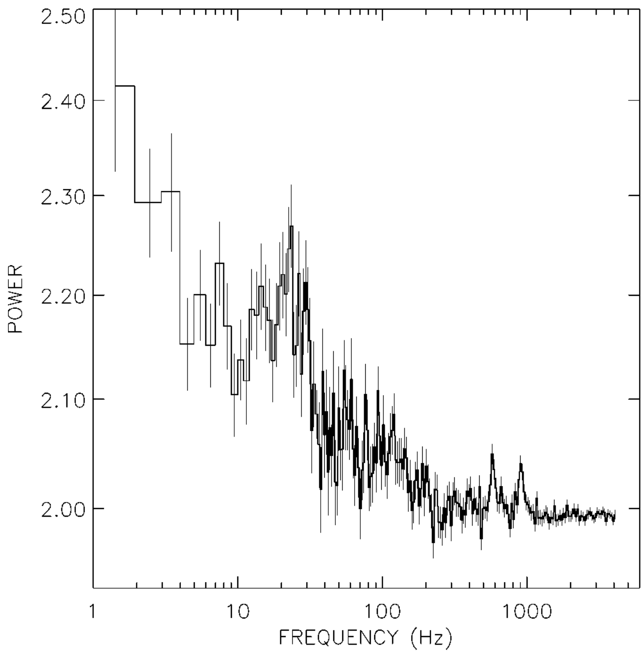

FIG. 1.—Power density spectra of 4U 0614+091 for the 2783 s interval beginning UTC 1996 April 25 4:58:23. Normalization of Leahy et al. (1983) has been used.

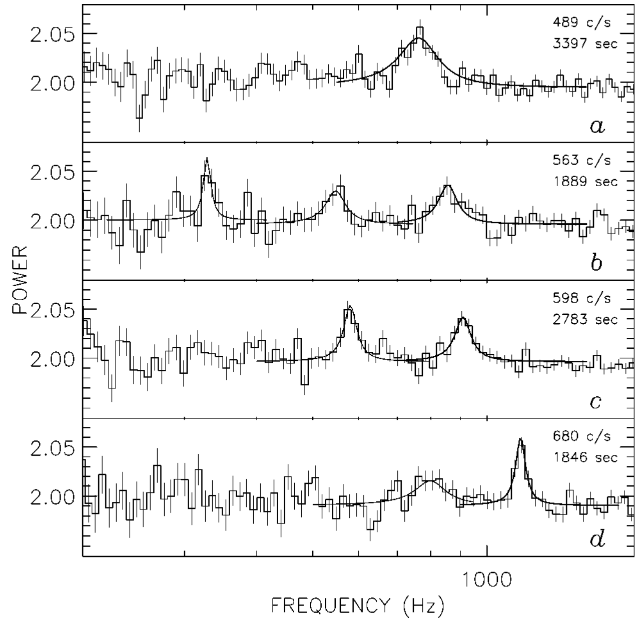

FIG. 2.—Power density spectra of 4U 0614+091 for five intervals beginning UTC 1996 April 25 0:10:23 (*a*), April 24 19:47:27 (*b*), April 25 4:58:23 (*c*), and August 6 20:52:01 (*d*). The observation time for each spectrum and the total count rates are given. Fits are shown to the high-frequency (*thick line*) and lower frequency (*thin line*) QPOs.

(e.g., very large event [VLE] triggers or sixfold anticoincidence triggers) are well correlated with the "good event" count rate. We calculate the linear fit of the VLE rate versus the good event count rate for standard mode 2 data from all the data in occultation for a given day in one of the Proportional Counter Units (PCUs). This is done using no channel cuts and matching the number of active PCUs in order to establish the calibration (in some intervals, only four of the five PCUs were active). The standard mode count rate is about 2 counts s^{-1} higher than the event mode rate since five fewer high-energy channels are used.We correct for this small difference. The calculated background rates agree to within approximately 10% with the current background estimates using layer subtraction in the PCA. The errors introduced by statistical uncertainty in the calibration to the VLE rates are small.

3. RESULTS

A typical power spectrum from a 2800 s interval is shown in Figure 1. The novel features of the power spectra are the peaks above 500 Hz. Figures 2 and 3 display the high-frequency portions of power spectra from various intervals. Two highly significant peaks are simultaneously present in the power spectra at high count rates (above approximately 400 counts s^{-1}). At lower rates, a single high-frequency peak is visible. We parameterize these peaks with Lorentzians, which provide good fits in all cases with typical χ^2_ν of approximately 1.

The frequency centroids of the QPOs are strongly dependent on the count rate, R, as shown in Figure 4. We identify a high- and low-frequency QPO whose motions in the (R, ν)-plane are clearly distinct. The R-ν relation of the QPOs from the April observation (Fig. 4) can be fitted by power laws with slopes, $d \log \nu / d \log R$, of 0.79 ± 0.09 (high-frequency peak) and 1.17 ± 0.10 (low-frequency peak). Linear fits are not statistically preferable. We note that the slopes of the power-law fits will be different if the two QPOs are separated by a constant frequency difference. Remarkably, in the August observations, the QPOs occupy a different place in the R-ν diagram. The count rates are smaller for a given frequency and deviate from a power-law relation at small R. Above approximately 550 counts s^{-1}, the correlation of R with ν in the August data can be fitted by power laws with exponents consistent with the April fits.

The fractional rms amplitude of the high-frequency QPO falls from approximately 12% at 400 counts s^{-1} to 6% at 600–700 counts s^{-1}. The rms amplitude of the low-frequency

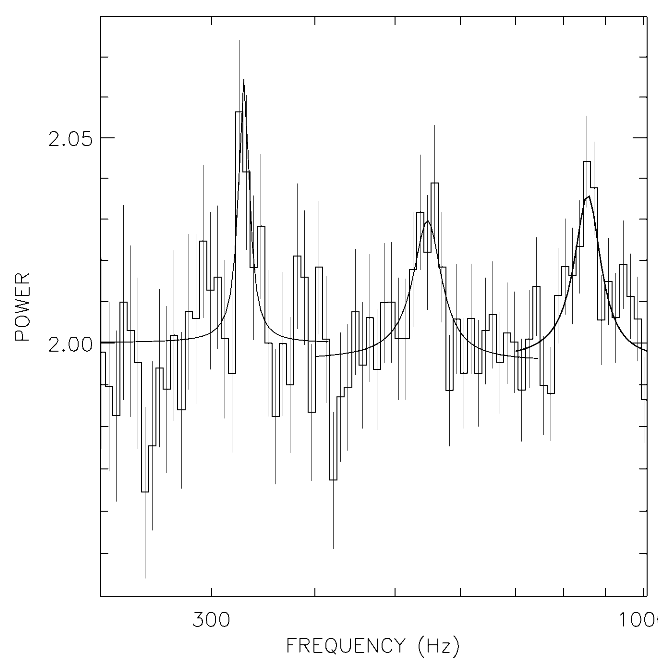

FIG. 3.—Power density spectra in the interval UTC April 24 19:47:27.

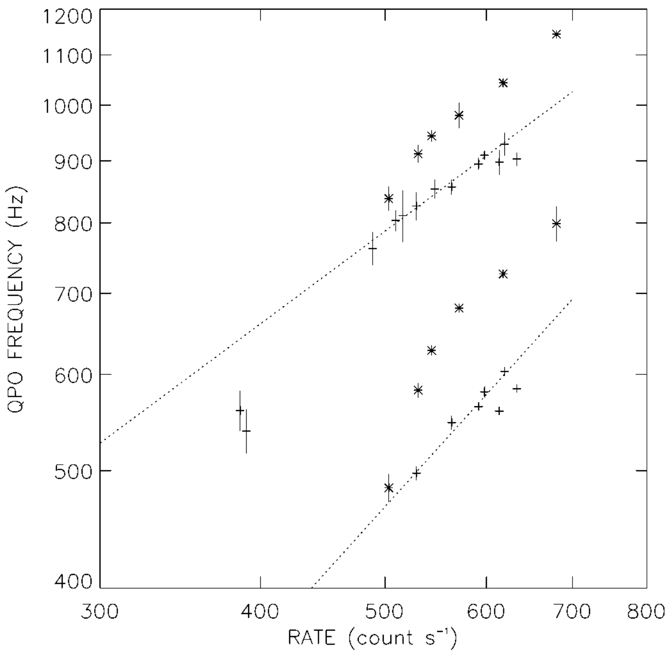

FIG. 4.—QPO centroid frequency vs. the total PCA count rate. The pluses are from the April data, and the asterisks are from the August data. Power-law relations are fitted to the QPO detections between UTC 1996 April 24 16:35:27 and April 25 5:44:46.

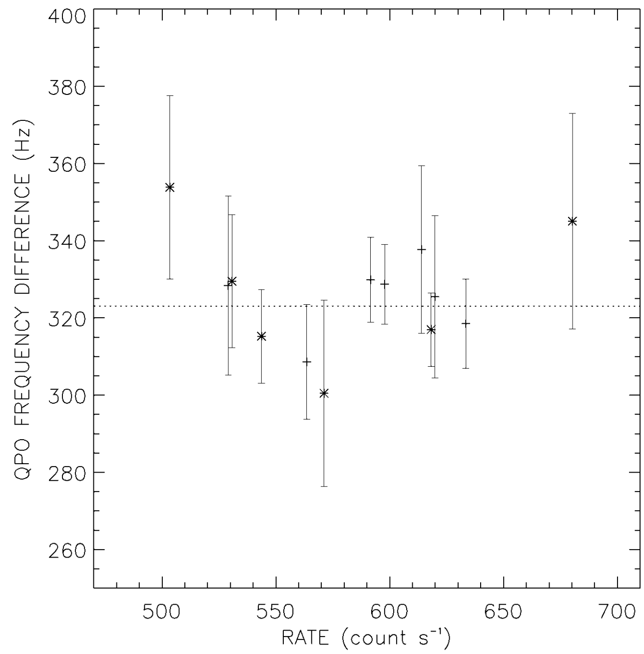

FIG. 5.—Frequency difference of the two simultaneously detected QPOs vs. the total PCA count rate. The pluses are from the April data, and the asterisks are from the August data. The mean frequency difference (*dotted line*) from all the data is 323 ± 4 Hz.

peak varies between 3% and 9% with no obvious count rate correlation. The quoted amplitudes are integrated over the full PCA band (1–100 keV); however, in practice, there is little detectable signal above about 12 keV. The measured Q-values (ν/FWHM) range from 5 to 20 for the higher frequency peak and from 10 to 40 for the low-frequency QPO. The Q-values increase somewhat as the count rate rises. However, the rate variations in each interval contribute significantly to these widths. Using the R-ν correlation to account for this contribution, we estimate that the intrinsic Q of both QPOs is in the range 10–20.

The difference between the frequency centroids of the two QPOs is remarkably constant within the errors (Fig. 5). The frequency difference from the April data is 325 ± 5 Hz. The frequency difference in the August observation, 321 ± 6 Hz, is consistent with that in April even though the QPOs clearly occupy a different region of the R-ν diagram. Taking all of the data together yields a mean frequency difference of 323 ± 4 Hz.

An additional feature was detected at 328 ± 2 Hz in the power spectrum from the interval beginning UTC 1996 April 24 19:47:27 (Fig. 3). The significance of this feature is 3.3 σ, as calculated relative to the flat background over a frequency interval centered on the maximum. We have conducted a search for other features in the power spectra in the 200–4000 Hz range and find that the only features with high significance are the QPOs discussed above and the 328 Hz peak in this interval. The two other QPOs in this interval are at 549 ± 7 and 858 ± 19 Hz. The 328 ± 2 Hz peak is significantly narrower than the higher frequency peaks (FWHM ~ 12 Hz, Q ~ 27). The frequency of the third peak is consistent with the difference in frequency of the 549 and 858 Hz peaks.

4. DISCUSSION

The detection of a constant frequency difference for the two high-frequency QPOs in observations separated by 3 months indicates clearly that there is a clock in this system that is stable on at least this timescale. The most likely candidate is a neutron star with an inferred spin period of 3.10 ± 0.04 ms. The spin period could also be twice this value, 6.2 ms, for certain magnetic field geometries. The narrow feature at 328 ± 2 Hz may be a direct detection of the neutron star spin period. The width of the feature might be a result of Doppler smearing due to orbital motion in a compact binary, for example.

The leading theory of the origin of low magnetic field millisecond radio pulsars has long been spin-up by accretion from a companion star (Alpar et al. 1982). LMXBs containing rapidly spinning, low magnetic field neutron stars are then the likely progenitors of millisecond pulsars. Our detection of a stable 3.1 ms period in 4U 0614+091, together with the detections of periods of 2.8 ms in 4U 1728−34 (Strohmayer et al. 1996) and 1.9 ms in KS 1731−260 (Morgan & Smith 1996), during X-ray bursts, provides the missing observational link in this evolutionary scenario.

A detailed discussion of mechanisms of QPO generation are beyond the scope of this Letter. However, we note that the magnetospheric beat-frequency model (Alpar & Shaham 1985) provides a framework for interpreting our observations. In such a model, there are three relevant frequencies in the system: the frequency of Keplerian orbits at the inner edge of the accretion disk ν_K, the spin frequency of the neutron star ν_S, and the difference between these frequencies—the "beat" frequency $\nu_B = \nu_K - \nu_S$. We identify the higher frequency peak (Fig. 2) with ν_K and the lower frequency peak with ν_B. The QPO frequencies vary as a result of a changing mass accretion rate that alters the accretion disk geometry. This simple model predicts that the frequency difference, $\nu_K - \nu_B$, is constant and is equal to the spin of the neutron star.

In the beat-frequency model, the inner edge of the accretion disk is taken to be the (accretion rate–dependent) magnetospheric radius (Alpar & Shaham 1985; Lamb et al. 1985; Ghosh & Lamb 1992). However, the simplest version of this model predicts a relation between the Keplerian frequency and the count rate, $\nu_K \propto R^\alpha$, with $\alpha = 3/7$, while our observations show a significantly steeper power law and a deviation from the power law at low count rates.

We note that the QPO frequencies are not uniquely determined by the source count rate. For a given count rate, the QPOs in the April versus August observations are observed at different frequencies (Fig. 4). This suggests that either the count rate and mass accretion rate are not simply related or that another parameter influences the QPO behavior.

Recently, Miller, Lamb, & Psaltis (1996) have considered a model in which QPOs are generated at the sonic point in the accretion disk flow, and a radiation feedback mechanism drives the beat-frequency signal. This model seems adequate to explain the large coherence and large rms amplitudes. In this model, the higher frequency QPO is also identified with a Keplerian orbital frequency.

Two high-frequency QPOs with a varying frequency difference have been observed from the *Z*-source Scorpius X-1 (van der Klis et al. 1996a). The variation of the frequency difference in Sco X-1 is in marked contrast to the constant frequency difference for 4U 0614+091. The rms amplitudes of the QPOs in Sco X-1 are significantly smaller (approximately 1%) than those in 4U 0614+091, and Sco X-1 has a much higher luminosity (close to Eddington) and probably a higher magnetic field. These differences suggest different origins of the QPOs in Sco X-1 and 4U 0614+091. We note that the photon bubble oscillation model (e.g., Klein et al. 1996) being applied to high-luminosity and high-field sources such as Sco X-1 does not have a natural means to produce a QPO frequency difference that is constant on a timescale of months, as observed in 4U 0614+091.

The behavior of the QPOs in 4U 0614+091 are apparently most similar to those in the atoll source 4U 1728−34 (Strohmayer et al. 1996). Two QPOs are observed from 4U 1728−34 at approximately the same frequencies scaling with count rate over a wide dynamic range. However, the QPOs in 4U 1728−34 appear at a higher count rate and may have a steeper R-ν correlation.

If the highest frequency QPO is identified as a Keplerian orbital frequency, then our measurement of a frequency centroid of 1144.7 ± 9.6 Hz for the 1800 s interval beginning 1996 August 6 20:52:01 UTC can be used to constrain the mass and radius of the neutron star in 4U 0614+091. In a Schwarzschild spacetime (an adequate approximation given the 3.1 ms period of the neutron star), no stable orbits exist within a radius of $6GM/c^2$. Observation of an orbital frequency ν_K then places an upper limit on the mass of the compact object of $M = c^3(12\sqrt{6}\,\pi G\nu_K)^{-1} = 2.2\ M_\odot(\nu_K/1000\ \mathrm{Hz})^{-1}$. Therefore, the mass of the neutron star in 4U 0614+091 must be less than 1.9 $M_\odot$. The radius of a circular orbit is simply $r = (GM/4\pi^2\nu_K^2)^{1/3}$, which implies an upper limit on the neutron star radius of 17 km for a mass of 1.9 $M_\odot$. We note that disruption of the accretion disk flow at the marginally stable orbit (Paczyński 1987) would cause the frequency versus count rate relation (e.g., Fig. 4) to flatten above a critical frequency (Miller et al. 1996). It is interesting to note that the maximum frequencies observed in the sources 4U 0614+091, 4U 1636−536 (van der Klis et al. 1996b), and 4U 1728−34 are all comparable and would imply neutron star masses of 1.9 $M_\odot$. Additional observations of these sources, particularly in high-luminosity states, may provide strong constraints on the properties of neutron stars.

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