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 XTE. 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%. At high count rates, two high frequency QPOs are detected simultaneously. The difference of their frequency centroids is consistent with 323 Hz in all observations. During one interval a third signal is detected at 328 ± 2 Hz. This suggests the system has a stable 'clock' which is most likely the neutron star with spin period 3.1 msec. Thus, our observations and those of another neutron star system by Strohmayer et al. (1996) 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 (Alpar et al. 1982). We suggest that the kinematics of the magnetospheric beat-frequency model (Alpar and Shaham 1985) applies to these QPOs. In this interpretation the high frequency signal is associated with the Keplerian frequency of the inner accretion disk and the lower frequency 'beat' signal arises from 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

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1. Introduction

High frequency quasi-periodic oscillations (QPOs) have now been discovered with XTE in at least seven 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 time scale 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 and evolution 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). Its luminosity and color behavior make it a probable atoll source (Singh and Apparao 1995). 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 XTE observations of 4U 0614+091 constitute the most extensive data set of this new phenomenon to date. We have measured the QPOs over a wide range in frequency from 480 Hz to 1150 Hz. Their behavior is relatively simple, being determined mainly by the source luminosity. The observations, analysis and results are discussed in Sections 2 and 3. In Section 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 Rossi X-ray Timing Explorer (Bradt et al. 1993) for 10 ks starting UTC 4/22/96 19:18:43, 33 ks beginning 4/24/96 13:18:37, and 16 ks beginning 8/6/96 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 SAA passages.

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) due to an instrumental deadtime 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 to 150 c/s compared to a total source count rate of 400 to 700 c/s. We first note that in earth occultation, the background rejection channels returned as PCA data products (e.g. Very Large Event triggers, 'VLE', or 6-fold anti-coincidence triggers) are well correlated with the good count rate. We calculate the linear fit of 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 PCUs. This is done using no channel cuts and matching the number of active PCUs to establish the calibration (in some intervals only four of the five PCUs were active). The Standard Mode count rate is about 2 c/s higher than the Event Mode rate since 5 fewer high energy channels are used. We correct for this small difference. The final result is a background rate estimate for the Event Mode data in 16 second intervals, which we use to calculate the source count rate. The errors introduced by statistical uncertainty in the background calibration 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. Figure 2 displays 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 c/s). 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_ν^2 of approximately 1.

The frequency centroids of the QPOs are strongly dependent on the count rate, R, as shown in Figure 3. We identify a high and low frequency QPO whose motions in the R vs ν plane are clearly distinct. The R vs ν relation of the QPOs from the April observation (Figure 3) can be fit be 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. In the August observation the QPOs occupy a different place in the R vs ν diagram. The count rates are smaller for a given frequency and deviate from a power law relation at small R. Above approximately 550 c/s, the correlation of R with ν in the August data can be fit 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 c/s to 6% at 600 to 700 c/s. The RMS amplitude of the low frequency peak varies between 3% and 9%. The measured Q values (ν/FWHM) range from 5 to 20 for the higher frequency peak and 10 to 40 for the low frequency QPO. 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 Q values increase somewhat as the count rate rises, while the FWHM of the QPOs decreases.

The difference between the frequency centroids of the two QPOs is remarkably constant (Figure 4). 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 vs ν diagram. Taking all of the data together yields a mean frequency difference of 323 ± 4 Hz.

An additional peak is detected at 328 ± 2 Hz during the interval beginning UTC 4/24/96 19:47:27 (Figure 2). This is detected at a significance greater than 3σ and is the only such feature in the power spectra from 200 Hz to 4000 Hz other than the QPOs discussed above. During this interval the two other QPOs are at 549 ± 7 Hz and 858 ± 19 Hz. The 328 ± 2 Hz peak is significantly narrower (FWHM ~ 12 Hz) than the higher frequency peaks. 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 three months clearly indicates that there is a clock in this system which is stable on at least this time scale. The most likely candidate is the neutron star with an inferred spin period of 3.10 ± 0.04 msec.

The narrow feature at 328 ± 2 Hz may be a direct detection of the neutron star spin period. The lack of coherence may be due to reprocessing of the radiation (Strohmayer et al. 1996).

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 low magnetic field neutron stars are then the progenitors of millisecond radio pulsars and should contain fast pulsars. Our detection of a stable 3.1 ms period in 4U 0614+091, together with the detection (Strohmayer et al. 1996) of a 2.8 ms period in 4U 1728-34 (GX 354-0), provide the missing link in this evolutionary scenario: direct evidence for millisecond pulsars in LMXBs.

A detailed discussion of mechanisms of QPO generation are beyond the scope of this paper. However, we note that the kinematics of a magnetospheric beat-frequency model (Alpar and Shaham 1985) gives an adequate account of the frequencies observed. 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 (Figure 2) as ν_K and the lower frequency peak as ν_B. The frequency of each signal varies as result of a changing mass accretion rate which alters the accretion disk geometry. This 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 and Shaham 1985, Lamb et al. 1985, Ghosh and 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.

Recently, Miller et al. (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, large RMS amplitudes, and steep R vs ν relation of the high frequency QPOs. 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 Sco X-1 (van der Klis et al. 1996a). The variation of the frequency difference in this source is in marked contrast to the constancy of the frequency difference over a broad span in time and luminosity in 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 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 which is constant on time scale 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 vs 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 8/6/96 20:52:01 UTC can be used to constrain the mass and radius of the neutron star in 4U 0614+091. In a Schwarzschild space-time (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 $M = c^3(12\sqrt{6}\pi G\nu_K)^{-1} = 2.2M_\odot(\nu_K/1000\,\mathrm{Hz})^{-1}$. Therefore, the mass of the neutron star in 4U 0614+091 must be less than $1.9M_\odot$. 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 $1.9M_\odot$. We note that disruption of the accretion disk flow at the marginally stable orbit (Paczynski 1987) would cause the frequency versus count rate relation (e.g. Figure 3) 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), 4U 1734-28 are all comparable and would imply a neutron star masses of $1.9M_\odot$. Additional observations of these sources, particularly in high luminosity states, may provide strong constraints on the properties of neutron stars.

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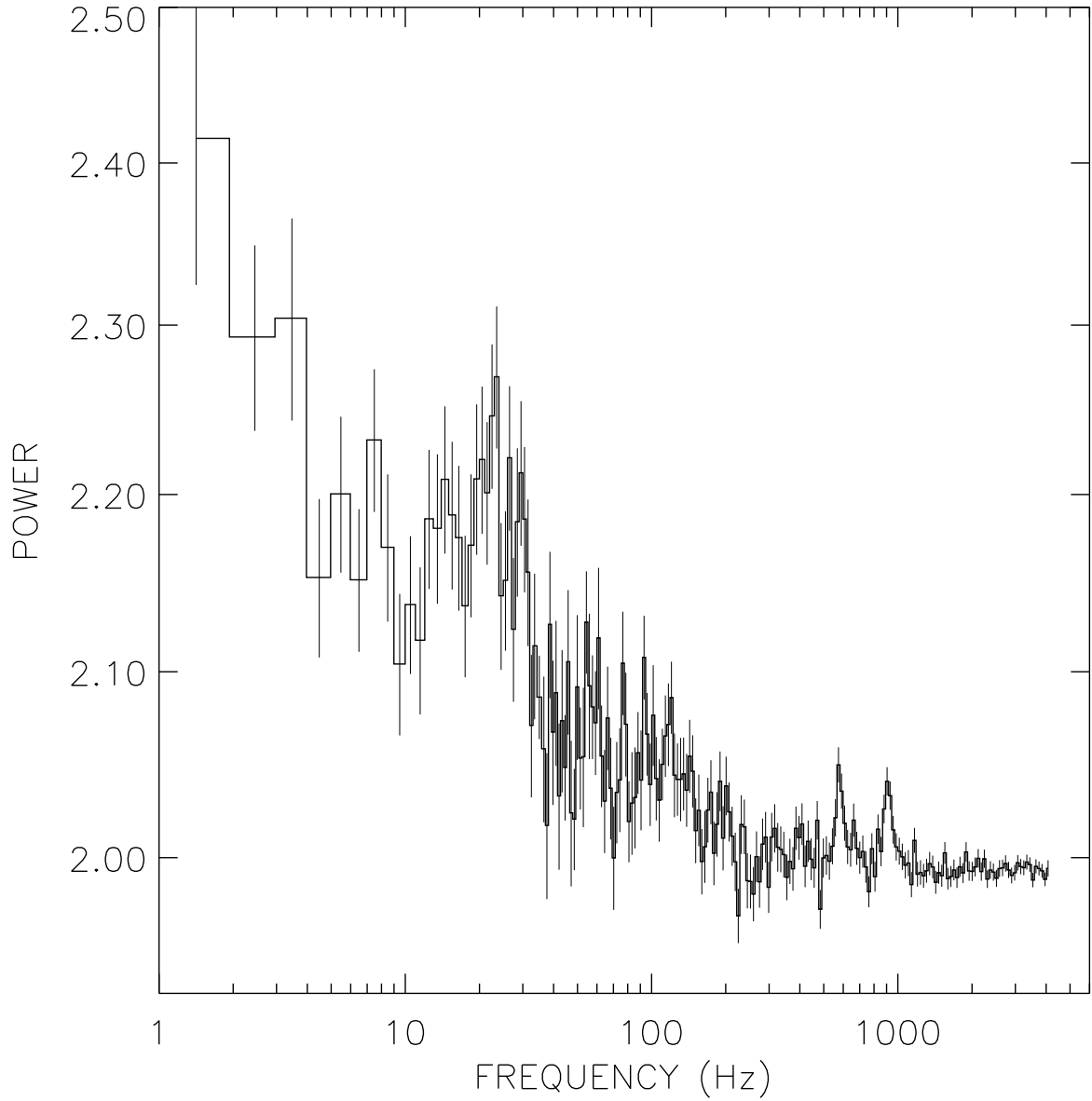van der Klis, M. et al. IAU Circ. 6428 (1996b)

Fig. 1.— Power density spectra of 4U 0614+091 for the 2783 s interval beginning UTC 4/25/96 4:58:23. Normalization of Leahy et al. (1983) has been used.
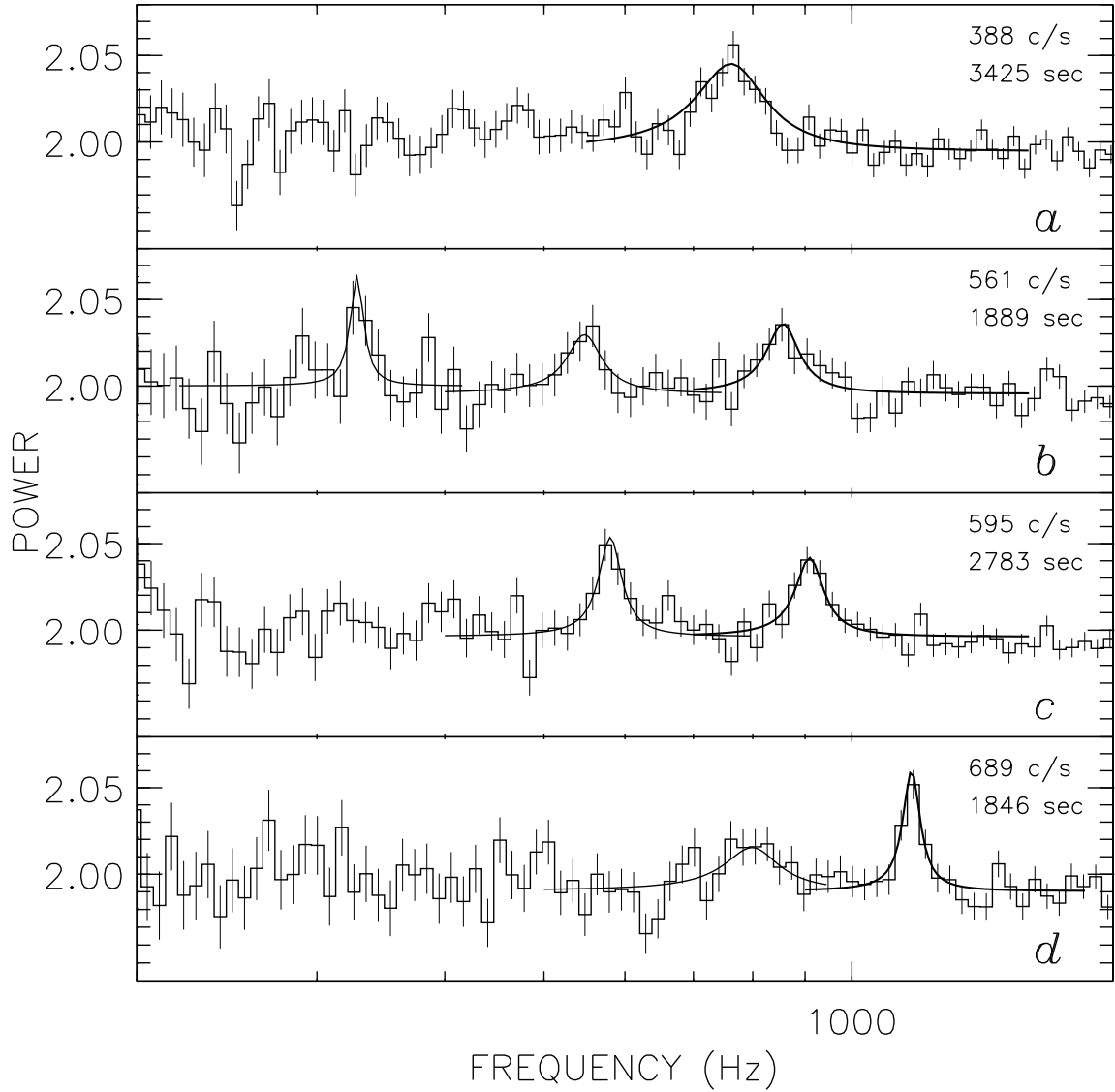
Fig. 2.— Power density spectra of 4U 0614+091 for five intervals beginning UTC 4/25/96 0:10:23 (a), 4/24 19:47:27 (b), 4/25 4:58:23 (c), and 8/6 20:52:01 (d). The observation time for each spectrum and the total count rates are given. Fits are shown to the high frequency (thick line) and lower frequency (thin line) QPOs.
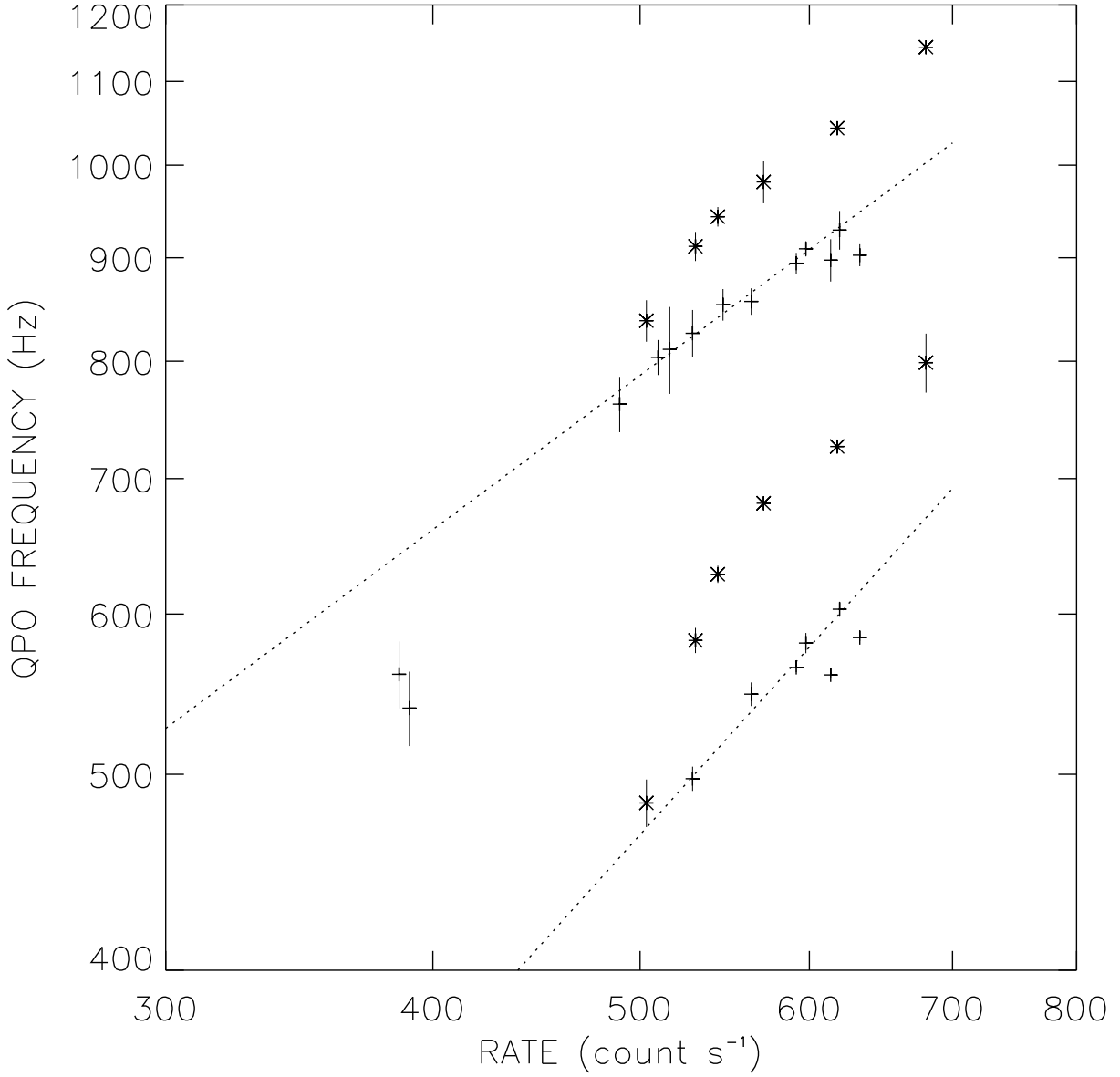
Fig. 3.— QPO centroid frequency versus the total PCA count rate. The pluses are April data, and the asterisks are August data. Power law relations are fit to the QPO detections between UTC 4/24/96 16:35:27 and 4/25/96 5:44:46.
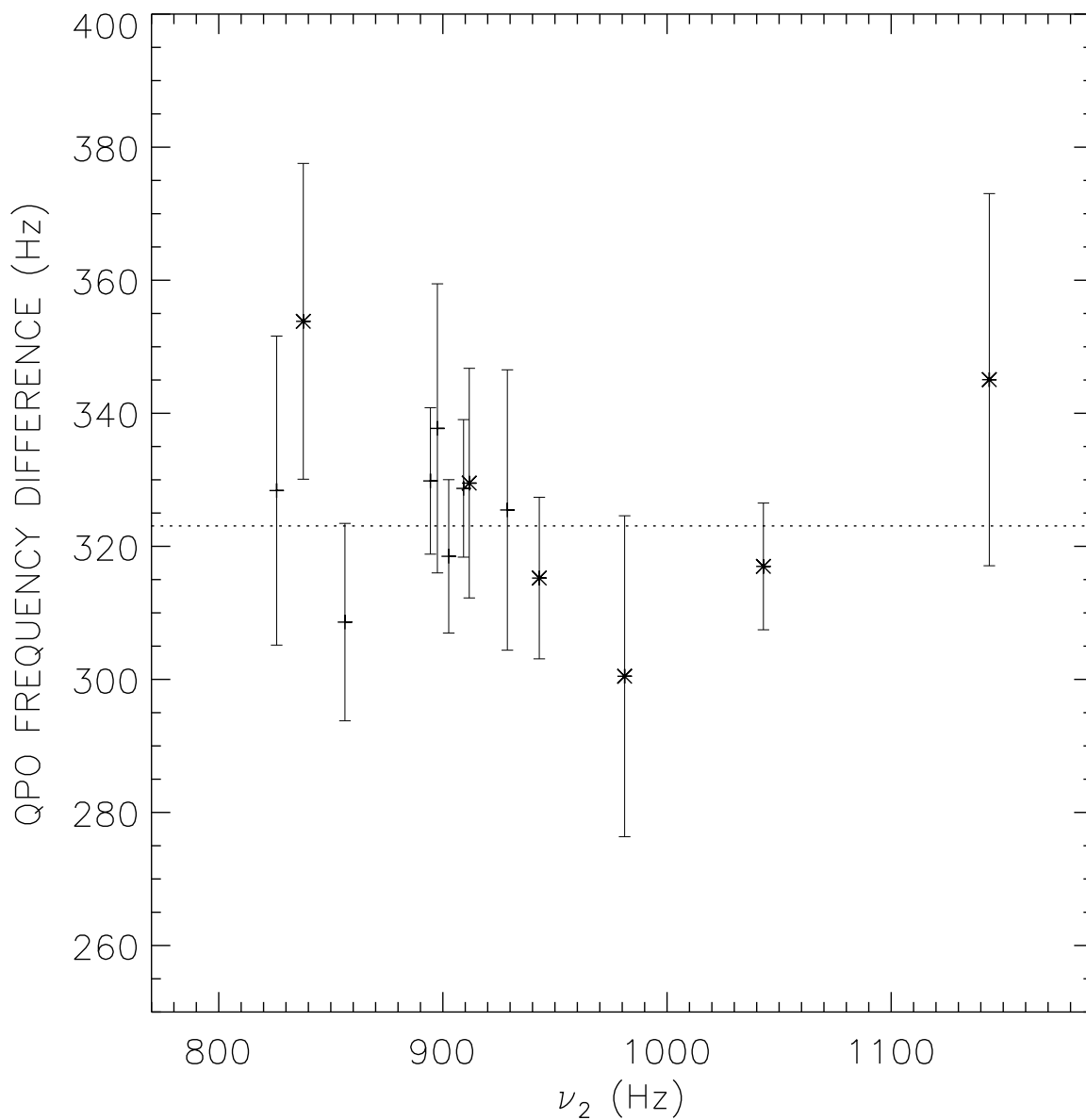
Fig. 4.— Frequency difference of the two simultaneously detected QPOs vs the frequency centroid of the higher frequency QPO. The pluses are April data, and the asterisks are August data. The mean frequency difference (dotted line) from all the data is 323 ± 4 Hz.