Energy Spectra and High Frequency Oscillations in 4U 0614+091

E.C. Ford[1], P. Kaaret[1], K.Chen[1], M.Tavani[1], D. Barret[2,3], P. Bloser[3], J. Grindlay[3], B.A. Harmon[4], W.S. Paciesas[5,4], and S.N. Zhang[6,4]

ABSTRACT

We investigate the behavior of the high frequency quasi-periodic oscillations (QPOs) in 4U 0614+091, combining timing and spectral analysis of RXTE observations. The energy spectra of the source can be described by a power law ($\alpha \sim 2.8$) and a blackbody ($kT \sim 1.5$), with the blackbody accounting for 10–20% of the total energy flux. We find a robust correlation of the frequency, ν, of the higher frequency QPO near 1 kHz with the flux of the blackbody, F_{BB}. The slope of this correlation, $d \log \nu / d \log F_{BB}$, is 0.27 to 0.37. The source follows the same relation even in observations separated by several months. The QPO frequency does not have a similarly unique correlation with the total flux or the flux of the power law component. The RMS fraction of the higher frequency QPO rises with energy from $6.8 \pm 1.5\%$ (3–5 keV) to $21.3 \pm 4.0\%$ (10–12 keV). For the lower frequency QPO, however, it is consistent with a constant value of $5.4 \pm 0.9\%$. The results may be interpreted in terms of a beat frequency model for the production of the high frequency QPOs.

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

[1]Department of Physics and Columbia Astrophysics Lab, Columbia University, 538 W. 120th Street, New York, NY10027
[2]Centre d'Etude Spatiale des Rayonnements (CESR), 9 Avenue du Colonel Roche BP4346, 31028 Toulouse Cedex 4, FRANCE
[3]Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
[4]NASA/Marshall Space Flight Center, ES 84, Huntsville, AL 35812
[5]University of Alabama in Huntsville, Department of Physics, Huntsville, AL 35899
[6]Universities Space Research Association/MSFC, ES 84, Huntsville, AL 35812

1. Introduction

Recent observations with the Rossi X-ray Timing Explorer (RXTE) have revealed quasi-periodic oscillations (QPOs) at high frequencies in numerous low mass X-ray binaries (see van der Klis 1997a, Ford et al. 1997b). These oscillations are likely produced within a few stellar radii of the surface of the neutron star; a typical frequency of 1000 Hz corresponds to an orbital radius of 15 km for matter in Keplerian motion around a $1.4 M_{\odot}$ neutron star. The behavior of these QPOs is yielding information on fundamental properties of the neutron stars: measurements of their spin periods (Strohmayer et al. 1996, Ford et al. 1997a) and masses (Kaaret, Ford, & Chen 1997; Zhang, Strohmayer, & Swank 1997b) and constraints on their radii (Miller, Lamb & Psaltis 1997). High frequency QPOs may also serve as unique probes of strong field general relativity (Kaaret, Ford, & Chen 1997).

One area of analysis, which has not been exploited to date, is the study of the energy spectra. Combining the spectral behavior with the QPO properties may prove particularly fruitful. Here we present such an analysis for 4U 0614+091, one of the X-ray bursters with strong QPOs near 1000 Hz (Ford et al. 1997a, Mendez et al. 1997). Section 2 is a description of the observations and the results of the energy spectral analysis. In Section 3 we correlate the spectral fits with the QPO behavior. In Section 4 we interpret these results in the context of a magnetospheric beat frequency model.

2. Observations and Spectral Analysis

RXTE observations of 4U 0614+091 were conducted on 22 and 24 April and 7 and 8 August 1996 for a total usable time of 79 ksec. Details of the observations and analysis of the high frequency QPOs are presented in Ford et al. (1997a). RXTE has two coaligned pointed instruments. The proportional counter array (PCA) consists of five separate proportional counter units (PCUs) with a large effective area from about 2 to 20 keV peaking at about 7000 cm^2. Each PCU consists of three Xe layers stacked behind a propane veto layer. The second pointed instrument, HEXTE, is a NaI array and extends energy coverage from 15 to 100 keV.

The accuracy of the spectral fits is currently dominated by systematic errors. We have found that the largest of these are the uncertainties in the PCU detector response matrices. Using various recent matrices, for example, we find that the total flux of the fitted spectra can change by 30%. Here we use the latest available matrices (Jahoda et al. 1997), which have been tested using the Crab continuum and the Fe line from Cas A.

We fit all five PCUs simultaneously and allow a varying normalization factor between detectors. We also use only the topmost Xe layer in which the source rates are highest, though the fits do not depend sensitively on which layers are used. We use the background estimation in the PCU based on particle activation and cosmic background (Stark et al. 1997). The background subtraction for the HEXTE detectors is based on the on-source, off-source rocking of the detectors.

A typical spectral fit from 4U 0614+091 is summarized in Table 1. We consider here a two-component continuum model consisting of a power law (PL) and blackbody (BB). This is an appropriate description of the continuum; such models have been used for X-ray binaries (White, Stella and Parmar 1988, Christian & Swank 1997), and previous observations of 4U 0614+091 with EXOSAT (Singh and Apparao 1994, Barret and Grindlay 1994) and Einstein SSS (Christian, White and Swank 1994) have suggested a BB plus PL model with similar values of PL index, BB temperature, and fluxes.

The BB plus PL description can be compared to other available continuum models, though a strict comparison using χ^2 statistics is not possible at this time since the fits are dominated by details of the detector response matrices. It is possible to artificially reduce the χ^2 values by adding an extra error (e.g. 1%) to each energy bin. We have not done this. Single component models, such as a BB or PL (Table 1), are less appropriate than the BB plus PL, as there are larger residuals with peculiar shapes and the χ^2 are larger. Other models are also less favored: a modified disk blackbody (Stella and Rosner 1984) and the disk model of Mitsuda et al. (1984) produce large residuals at low and high energies in the PCA, and have χ^2/ν values of 3065/259 and 12345/258 respectively. A Compton scattering model (Sunyaev and Titarchuk 1980) provides a somewhat better fit, but still yields $\chi^2/\nu = 2758/258$.

Over our observations (more than 25 orbits), 4U 0614+091 shows significant variability. The flux of the PL component covers the range $17.1 - 24.0 \times 10^{-10}$ erg cm^{-2} s^{-1} (1–20 keV), with typical errors of 5% while the

BB flux varies from $1.5-6.4\times10^{-10}$ erg cm^{-2} s^{-1} (errors of $\sim$3%), which is 8 to 21 % of the total flux. As the BB flux increases, the photon index of the power law softens from 2.62 to 3.17 (typical error 0.02). This trend is opposite to the one expected if the two components are actually just a non-physical description of the continuum shape. For an accidental coupling, we would expect the blackbody flux to increase as the powerlaw hardens to take over the missing flux at low energy.

We are excluding here the data during 22 April and 8 August observations. In these intervals the blackbody components have low fluxes (less than about 1×10^{-10} erg cm^{-2} s^{-1}) and are cool ($kT < 0.7$ keV) and not well determined in the PCUs, as we impose a lower energy bound of 2 keV due to the poor response of the PCUs at low energy. Spectral parameters for these intervals have proven unreliable.

Adding interstellar absorption can change the flux of the blackbody by as much as 5%. The value of equivalent hydrogen column density, n_H, is not well determined due to the cutoff at 2 keV. We therefore fix n_H at 0.18×10^{-22} cm^{-2}, a value consistent with the previous observations (Christian, White & Swank 1994). In establishing errors we have allowed n_H to vary between $0.13-0.23\times10^{-22}$ cm^{-2}, a range that encompasses the values from previous observations.

The spectral fits in all observations are improved with the addition of a narrow line at an energy of about 7 keV. A feature at the same energy has also been identified in the EXOSAT data (Singh and Apparao 1994). We have not included this line in the fits quoted here, but the results below do not depend sensitively on whether this line is included.

The fits are also insensitive to the inclusion of HEXTE data. We quote results here including the HEXTE data, but removing HEXTE changes the fluxes and fit parameters by less than 1%.

3. Correlation of Spectral and Timing Variations

The two high frequency QPOs in 4U 0614+091 are simultaneously present in most observations and are separated in frequency by 323 Hz (Ford et al. 1997a). Here we focus mainly on the higher frequency QPO. Figure 1 shows that the higher QPO frequency, ν, correlates very well with the flux of the blackbody spectral component, F_{BB}.

The exact details of this correlation depend on the spectral fitting. In particular changing the response matrices changes the flux estimates. We note, however, that the correlation is apparent in all trials using different response matrices and models. We parameterize the correlation in terms of the slope, $\alpha = d\log\nu/d\log F_{BB}$. The fits in Figure 1 yield $\alpha = 0.29\pm0.01$. In our various spectral fitting trials, α is always in the range 0.27 to 0.37. The slope depends somewhat on the energy integration range used in calculating the BB fluxes. We have used a range 1–20 keV. Though this range extends to somewhat beyond the PCA window, using such a wide band makes α insensitive to the particular choice of energy cutoffs.

The higher QPO frequency clearly correlates well with BB flux. This is in contrast to the variations of QPO frequency with respect to count rate, R, where the August and April 1996 observations occupy two separate branches in the $R-\nu$ plane (Ford et al. 1997a). Figure 2 shows there is no unique correlation of frequency with total flux. Similarly the flux of the PL does not uniquely determine the QPO frequency. Thus, only the BB flux can be regarded as a good indicator of QPO frequency.

Figure 3 shows the energy resolved fractional RMS amplitude for both QPO features. The data are taken from an interval with one of the stronger QPO detections. The fractional amplitude of the higher frequency QPO clearly rises up to about 12 keV, which indicates that the spectrum associated with the oscillation is harder than the time averaged spectrum. The fractional amplitude of the lower frequency QPO is approximately constant with energy. Figure 3 suggests that the two QPOs have different trends of RMS fraction with respect to energy. If the shapes are in fact distinguishable, then this different energy dependence may provide an independent diagnostic for identifying which of the two QPOs is present when only one QPO is observed from a source.

4. Discussion

The results of Section 3 show that the QPO frequency is uniquely determined by the flux of the blackbody component of the spectrum and not the total flux or the flux of the power law component. As a working hypothesis we consider a beat-frequency interpretation in which the higher frequency QPO is determined by the orbital Keplerian frequency of matter in the inner disk.

In the magnetospheric model (Alpar & Shaham

1985) the disk is interrupted by the pressure of the magnetosphere (Ghosh & Lamb 1979), and the Keplerian frequency and luminosity scale as $\nu_K \propto L^{\alpha}$. If the luminosity is released at the neutron star surface, then the value of α is 3/7. If the energy is liberated mainly at the magnetospheric boundary, then $\alpha = 1/3$ (Alpar and Shaham 1985, Lamb et al. 1985). These numbers are derived assuming a pure magnetic dipole field and a simple form for the luminosity. Our determination of $\alpha = 0.27$ to 0.37 is remarkably close to these simple estimates. The measurement, however, is not sufficiently well constrained to distinguish between the two predictions for α.

The correlation of QPO frequency with blackbody flux indicates that the radius of the inner disk is related to the blackbody flux. Both the blackbody flux and the inner disk radius, apparently, are determined by the mass accretion rate through the disk. This picture is consistent with the behavior of the inferred size of the emission region. The size grows as the flux and frequency increase. This is as expected since the x-ray emitting area of the disk increases in size as the inner disk radius shrinks.

The emission in the QPO itself, however, is probably not from the blackbody. This is because the RMS fraction increases at higher energies, which means that the QPO emission is harder than the average spectrum. Given the correlation of QPO frequency with blackbody flux, this might seem paradoxical. We note, however, that the blackbody flux may track the QPO frequency (by a common dependence on mass accretion rate for instance) while not actually producing the photons in the modulation.

The QPO photons are more likely associated with the emission in the power law component. The power law component, which carries most of the energy, could be produced in the inner-most regions as matter falls from the inner disk edge to the neutron star surface (Kluzniak & Wagoner 1985). Alternatively, non-thermal magnetic effects may produce the power law (Tavani & Liang 1996).

The evidence for a beat frequency mechanism for the kiloHertz QPOs is compelling. In many atoll sources so far observed, high frequency QPOs are detected simultaneously at two frequencies. The difference in the frequencies of the two QPOs remains constant over a span of months, as confirmed in several sources (Ford et al. 1997a, Strohmayer et al. 1996). This is exactly as predicted by the beat frequency model; the higher frequency QPO is from Keplerian motion, and the lower frequency QPO is a modulated interference with the spin of the neutron star. The frequency difference between these two signals constant and equal to the neutron star spin frequency. Remarkably, a third signal has been detected during X-ray bursts in a few sources at a frequency equal to the difference frequency or a multiple of the difference (Strohmayer et al. 1996, Smith, Morgan & Bradt 1997, Wijnands & van der Klis 1997b). This suggests that the difference frequency is indeed the spin frequency of the neutron star. In 4U 1636-536 the frequency of oscillations discovered during a burst is marginally consistent with twice the difference frequency (Zhang et al. 1997a, Wijnands et al. 1997a). A QPO at the difference frequency has been reported in the quiescent emission of 4U 0614+091 (Ford et al. 1997a). The behavior of the high frequency QPOs in atoll sources is consistent with a beat frequency description.

A glaring exception to this behavior is the Z-source Sco X-1 (van der Klis et. al 1997b). In Sco X-1, the QPOs near 1 kHz are broadly similar to those in the atoll sources discussed above, but here the difference of the QPOs is not constant but decreases with increasing luminosity (van der Klis et al. 1997b). This would appear to be a case against the simple beat frequency model. Perhaps the effects of radiation are more important in Sco X-1 where the luminosity is about 100 times larger than in 4U 0614+091.

Recently QPOs near 1000 Hz were discovered in GX 5-1 (van der Klis et al. 1996) and GX 17+2 (van der Klis et al. 1997c), archetypal strong Z-sources which are known to have strong low frequency horizontal branch QPOs. These results put the original magnetospheric beat frequency model in an awkward position. The original model (Alpar & Shaham 1985, Lamb et al. 1985) was adopted to explain the 15 to 60 Hz horizontal branch oscillations in Z-sources. These bright sources were observed with only single QPOs, presumed to be the beat frequency. It is still puzzling that the other two frequencies implied by the model have never been observed. Both the kHz oscillations and the horizontal branch oscillations cannot arise at a single inner disk. The applicability of the models to horizontal branch oscillations needs further examination. Certainly, the conclusions and constraints on the beat frequency model from the horizontal branch QPOs should not be used against its application to high frequency QPO observations.

We would like to thank the staff of the RXTE Guest Observer Facility, in particular Keith Jahoda for discussion and support on the PCA response. This work was supported by a NASA RXTE grant and a NASA Graduate Student Researchers Program Award.

REFERENCES

Alpar, M.A., & Shaham, J., Nature, 316, 239-241 (1985)

Barret, D., and Grindlay, J.E., ApJ, 440, 841 (1994)

Christian, D.J.,White, N.E., and Swank, J.H., ApJ, 422, 791-798 (1994)

Christian, D.J. & Swank, J.H., ApJS, 109 177-224 (1997)

Ford, E. et al., ApJL, 475, L123-126 (1997a)

Ford, E.C. et al., http://www.astro.columbia.edu/˜ eric/qpos.html (1997b)

Ghosh, P. & Lamb, F.K., ApJ, 234, 296 (1979)

Jahoda, K., and the XTE/PCA team http://lheawww.gsfc.nasa.gov/docs/xray/xte/pca/ (1997)

Kaaret, P., Ford, E. & Chen, K., ApJL, 480, L27 (1997)

Kluzniak, W. & Wagoner, R.V. ApJ, 297, 548-554 (1985)

Lamb, F.K., Shibazaki, N., Alpar, M.A., & Shaham, J., Nature, 317, 681-687 (1985)

Mendez, M., et al., ApJ, accepted (1997)

Miller, M.C., Lamb, F., and Psaltis, D., submitted to ApJ (1997)

Mitsuda, et al. PASJ, 36, 741 (1984)

Singh, K.P., and Apparao, K.M.V., ApJ, 431, 826-835 (1994)

Smith, D.A., Morgan, E.H. and Bradt, H., ApJL, 479, L137 (1997)

Stark, M., and the XTE/PCA team, http://lheawww.gsfc.nasa.gov/docs/xte/pcabackest.html/ (1997)

Stella, L. and Rosner, R., ApJ, 277,312 (1984)

Strohmayer, T. et al., ApJL,469, L9-L12 (1996)

Sunyaev, R.A. and Titarchuk, L.G., AA, 86, 121 (1980)

Tavani, M. & Liang, E., A&ASS, 120, 133 (1996)

van der Klis, M. et al., IAU Circ. 6511 (1996)

van der Klis, M. et al., astro-ph/9704272 (1997a)

van der Klis, M. et al., ApJL, 481, L97 (1997b)

van der Klis, M. et al., IAU Circ. 6565 (1997c)

White, N.E., Stella, L., and Parmar, A.N., ApJ, 324, 363-378 (1988)

Wijnands, R.A.D. et al., ApJL, 479, L141 (1997a)

Wijnands, R.A.D. et al., ApJL, 482, L65 (1997b)

Zhang, W. et al., IAU Circ.6541 (1997a)

Zhang, W., Strohmayer, T. and Swank, J., ApJL, 482, L167 (1997b)

This 2-column preprint was prepared with the AAS LaTeX macros v4.0.

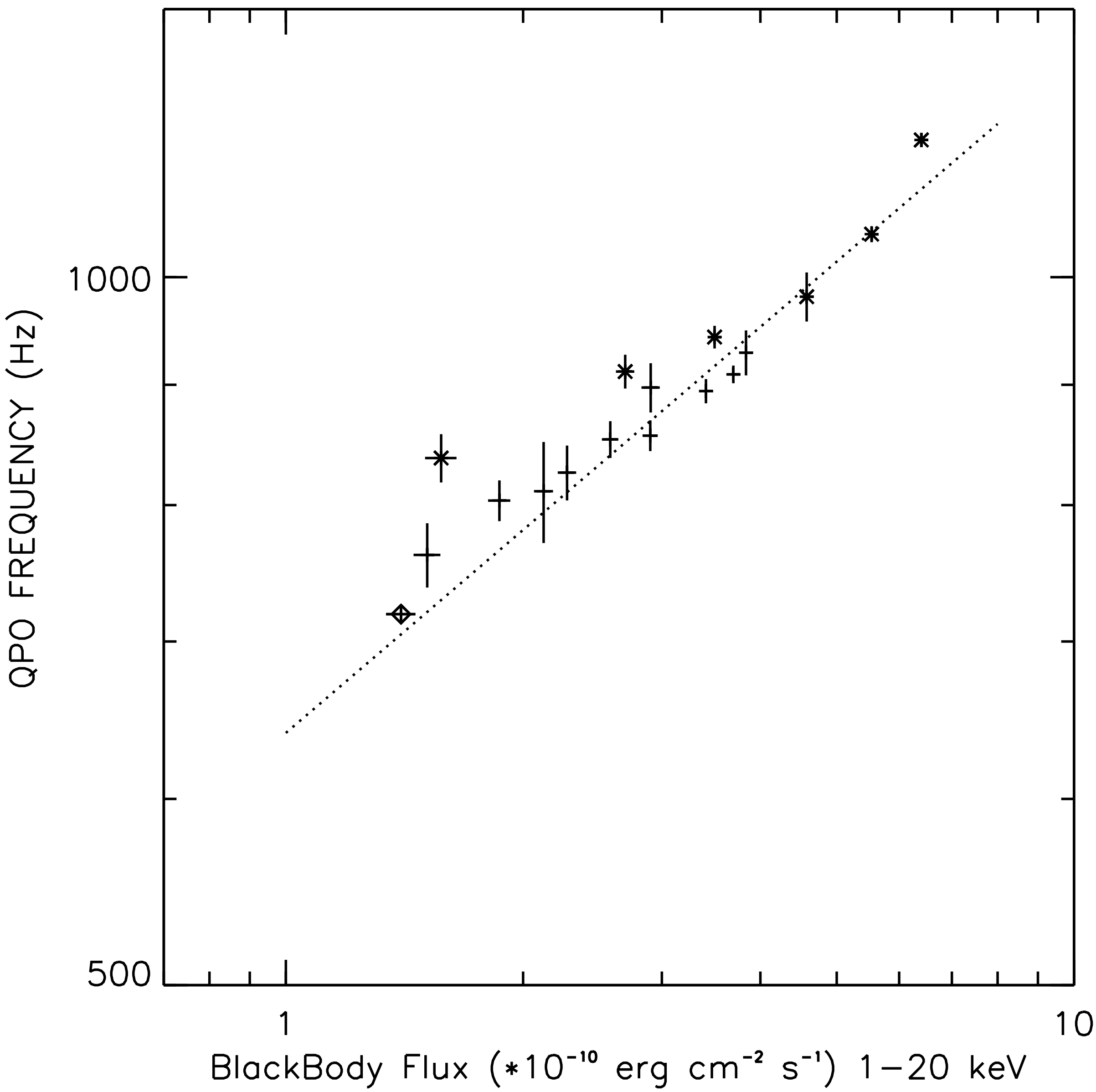

Fig. 1.— QPO frequency versus flux of the blackbody spectral component. The plusses are April data, and the asterisks are August data. The power law fit has a slope of $\alpha = 0.29 \pm 0.01$. The fluxes are from a spectral fit using a PL+BB function (Table 1), with equivalent hydrogen column density of 0.18×10^{-22} cm^{-2}. The errors plotted include all systematics except the variations due to changing the detector response matrices. The data point at 719 Hz (diamond) is from Mendez et al. (1997) and is not used in determining the power law fit.

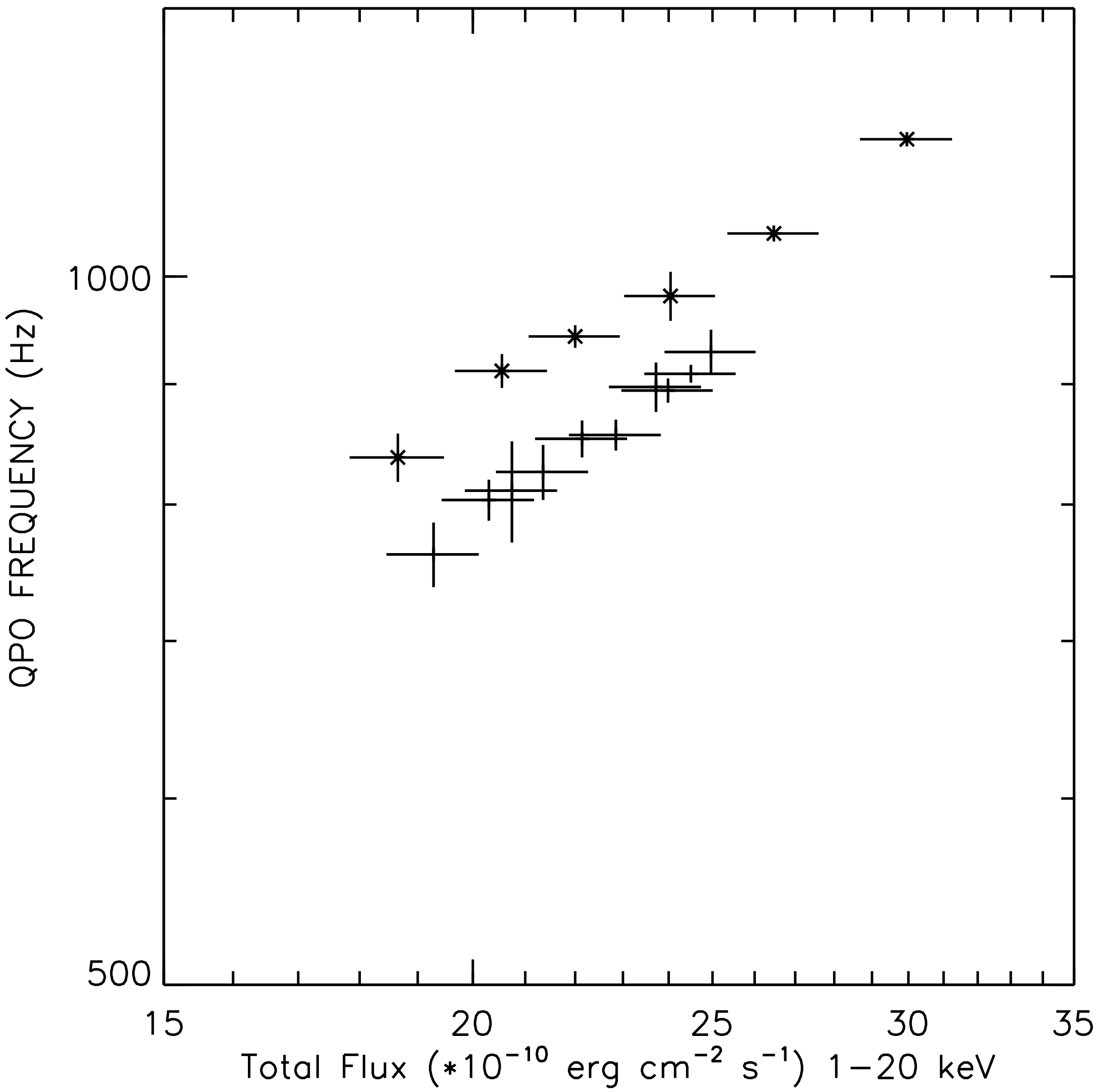

Fig. 2.— QPO frequency versus the total energy flux, based on the same fits as Figure 1. The plusses are April data, and the asterisks are August data. The April data can be fit by a power law with slope, $\alpha = 1.4 \pm 0.3$, while, for the August data, $\alpha = 1.6 \pm 0.2$.

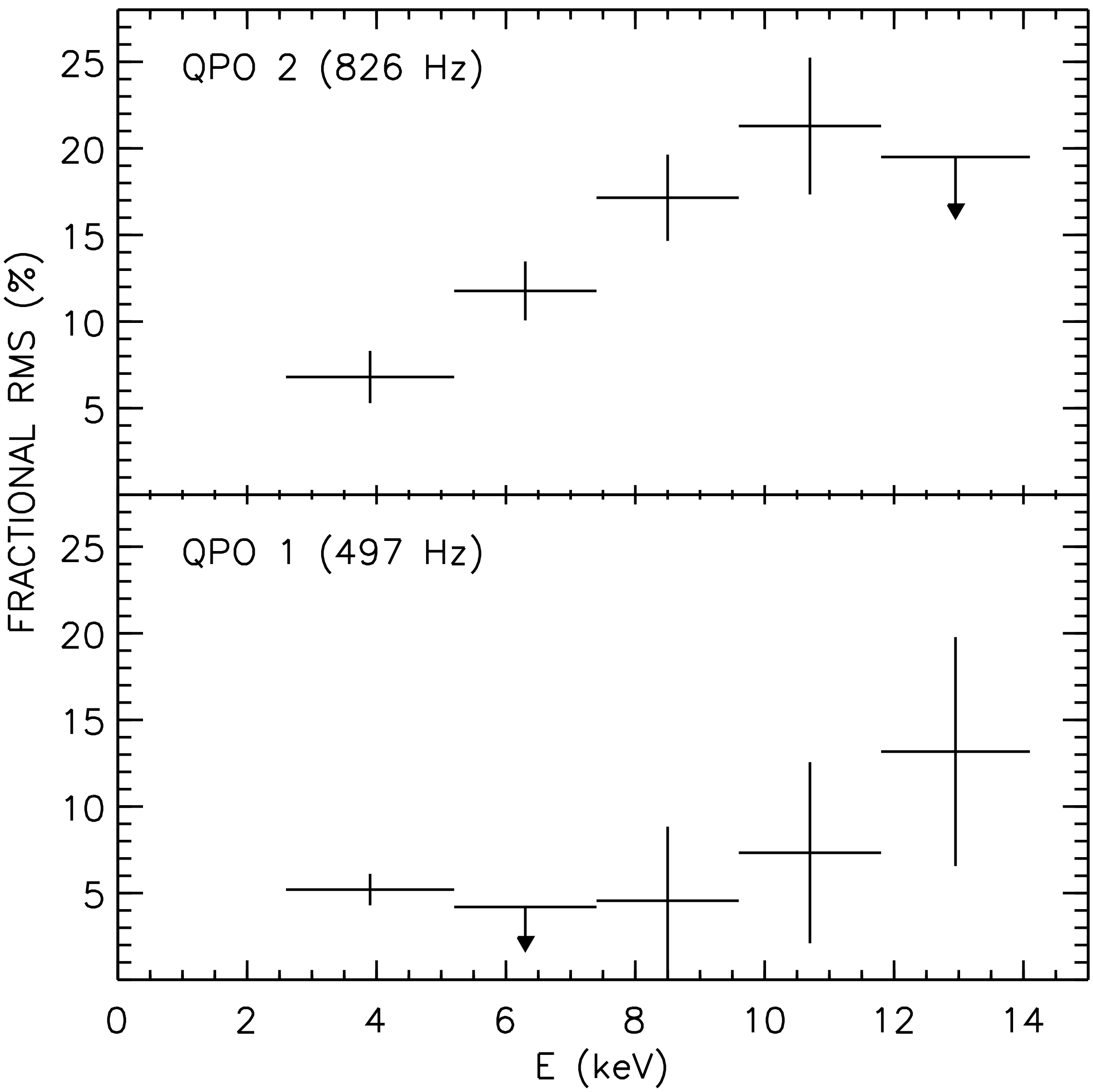

Fig. 3.— RMS amplitude vs. energy for the two QPOs detected in the interval beginning UTC 4/25/96 03:11:26. The top panel shows data for the higher frequency QPO, while the bottom panel is for the lower frequency QPO. Upper limits are 2σ.

TABLE 1
SPECTRAL FITS

MODEL	α	Norm	F_{PL}[a]	kT_{BB} (keV)	Norm	F_{BB}[a]	χ^2/dof
BB	...	...	...	1.244	1.29×10^{-2}	10.6×10^{-10}	78217/339
PL	2.615	1.063	23.3×10^{-10}	...	...	...	7545/339
PL + BB	2.787	1.073	19.8×10^{-10}	1.540	3.11×10^{-3}	2.58×10^{-10}	1491/318
error from n_H	0.017	0.043	0.95×10^{-10}	0.013	0.05×10^{-3}	0.06×10^{-10}	...
error from response	0.234	0.446	5.42×10^{-10}	0.171	0.28×10^{-3}	0.22×10^{-10}	...

NOTE.—Fits to the 2864 second interval beginning UTC 8/7/96 01:48:19. The equivalent hydrogen column density has been fixed at $n_H = 0.18 \times 10^{-22}$ cm^{-2}. The bottom two rows show the errors introduced in the PL+BB fit by 1) the different values of n_H and 2) the different response matrices used in the fit.

[a]Flux: erg cm^{-2} s^{-1} (1–20 keV).