X-ray Nova XTE J1550-564: Discovery of a QPO Near 185 Hz

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We have investigated the X-ray timing properties of XTE J1550-564 during 60 RXTE PCA observations made between 1998 September 18 and November 28. We detect quasi-periodic oscillations (QPOs) near 185 Hz during four time intervals. The QPO widths (FWHM) are $\sim 50$ Hz, and the rms amplitudes are $\sim 1\%$ of the mean flux at 2-30 keV. This is the third Galactic black hole candidate known to exhibit a transient X-ray timing signature above 50 Hz, following the 67 Hz QPO in GRS1915+105 and the 300 Hz QPO in GRO J1655-40. However, unlike the previous cases, which appear to show stationary frequencies, the QPO frequency in XTE J1550-564 must vary by at least $\sim 10\%$ to be consistent with observations. The occurrences and properties of the QPO were insensitive to large changes in the X-ray intensity (1.5 to 6.8 Crab). However, the QPO appearance was accompanied by changes in the energy spectrum, namely, an increase in the temperature and a decrease in the normalization of the thermal component. The QPO is also closely related to the hard X-ray power-law component of the energy spectrum since the fractional amplitude of the QPO increases with photon energy. The fast QPOs in accreting black hole binaries are thought to be effects of general relativity; however, the relevance of the specific physical models that have been proposed remains largely uncertain. Low frequency QPOs in the range 3-13 Hz were often observed. Occasionally at high luminosity the rms QPO amplitude was $\sim 15\%$ of the flux, a level previously reached only by GRS1915+105. These extraordinary oscillations have a coherence parameter $(\nu/\Delta \nu)$ in the range 4-12 and are tied to the power-law component in the energy spectrum.

*Subject headings:* black hole physics – stars: individual (XTE J1550-564) –
stars: oscillations – X-rays: stars
1. Introduction

The X-ray nova and black hole candidate XTE J1550-564 was first detected on 1998 September 6 (Smith et al. 1998) with the All Sky Monitor (ASM; Levine et al. 1996) aboard the Rossi X-ray Timing Explorer (RXTE). It is the brightest X-ray nova yet observed with RXTE. The ASM light curve and further background information for this source are provided in a companion paper by Sobczak et al. (1999b; hereafter paper I). Extensive observations of the optical counterpart are described by Jain et al. (1999; hereafter paper III). The 2.5-20 keV spectrum of XTE J1550-564 resembles the sources that are dynamically established to be black hole binaries. The X-ray and optical intensities of this source suggest a distance of roughly 6 kpc (paper I).

We present results from 60 RXTE observations of XTE J1550-564 that were made between 12 and 83 days after the outburst began. Results from earlier RXTE observations (outburst days 2–10) were reported by Cui et al. (1999), who found that during the initial rise (0.6–2.1 Crab) the source exhibited QPOs with a frequency that systematically increased from 0.08 to 8 Hz as the X-ray flux increased. These QPOs were very strong, with rms amplitudes typically $\sim 15\%$ of the mean flux over the full PCA band. In each observation, the QPO amplitude (rms / mean flux) increased by a factor of two between 2 and 30 keV. The temporal variability displayed by XTE J1550-564 also resembles some of the black hole systems observed during outburst (Cui et al. 1999; paper I).

Herein we show a series of power spectra in which there are frequent appearances of QPOs in the range 2-13 Hz. There are also a few occasions in which we detect a high frequency QPO near 185 Hz which is analogous to the stationary QPOs observed for two black hole candidates: GRS1915+105 (67 Hz; Morgan, Remillard, & Greiner 1997) and GRO J1655-40 (300 Hz; Remillard et al. 1999b).
2. Observations and Analysis

The times of the 60 RXTE pointed observations and a summary of some X-ray properties of XTE J1550-564 are given in Table 1 of paper I. We have analyzed the X-ray timing properties of XTE J1550-564 using data from the PCA instrument (Jahoda et al. 1996). Within the constraints of spacecraft telemetry, we obtained moderately good time resolution in at least a few energy bands by conducting the observations as follows. In most cases, the PCA Event Analyzers (EAs) were configured to deliver $122 \mu s$ time resolution in three broad energy bands, which are approximately 2-6 keV, 6-12 keV, and 12-30 keV. The 30 keV boundary is an effective limit imposed by the source spectrum, not by exclusion of high energy events in the data processing. Lower time resolution was occasionally used to avoid possible telemetry saturation due to high count rates: the time resolution was $250 \mu s$ for observations #4–6 (see paper I, Table 1) and $500 \mu s$ for observations #9–10. In parallel, we usually used a fourth EA to provide 8 energy bands with 4 ms time resolution within the energy range 2-13 keV.

For each PCA observation, we computed power spectra for each of the 3 energy bands sampled with high time resolution and also for the 2–30 keV sum band. Power spectra were computed for every 256 s data segment. Then for each observation and energy band, we averaged together all of the 256 s power spectra. We subtracted the contribution from counting statistical noise, corrected for dead-time effects as described by Morgan et al. (1997). The power spectra are normalized such that the power in each frequency bin is the square of the rms amplitude divided by the mean count rate. At high frequencies, residual continuum power $\lesssim 10^{-6} \text{ Hz}^{-1}$ is likely to represent inaccuracies in our subtraction of statistical noise, rather than source behavior.

We used a chi-squared minimization technique to derive the central frequency and the width of an X-ray QPO. We fit each QPO feature with a Lorentzian function, while the
continuum on both sides of the QPO was modeled with a power law function. On some occasions (e.g., see Sept 21a,b below), it was necessary to add a quadratic term to the relationship between log power density and log frequency, in order to adequately model the curvature in the power continuum. The QPO fit parameters include the QPO central frequency ($\nu$) and the full width at half maximum ($\Delta \nu$). The amplitude of the QPO, expressed as a fraction of the mean count rate, is the square root of the integrated power in the QPO feature. The central frequencies of the 2–13 Hz QPOs are included in Table 1 of Paper I, while the results for the fast (\(~185 \text{ Hz}\)) QPOs are given in Table 1 below.

3. Results

It can be seen in paper I that there are both short-term and long-term variations in the intensity, X-ray spectrum, and QPO properties of XTE J1550-564. Furthermore, the changes in timing and spectral parameters are highly correlated (see Table 1 of paper I). To facilitate our sensitivity to the high frequency QPOs, we average together power spectra from sequential time intervals in which the changes in source behavior are relatively minor. There are 12 such groups, and their power spectra are shown in Figure 1. The averaging has smeared the low frequency QPOs (3–7 Hz) in panels d–g of Figure 1, as can be discerned from Table 1 of paper I, but this does not alter our conclusions below.

In our observations of 1998 September and October, XTE J1550-564 is bright in X-rays with 2-30 keV intensity above 0.5 Crab. The majority of the power spectra during this interval show a continuum that is relatively flat below a few Hz; the power density values (\(~0.01\)) imply \(~10\%\) rms variations at timescales longer than \(~0.2 \text{ s}\). There is a sharp break in the continuum power near 5–10 Hz, with a QPO feature near or somewhat above the break frequency. A second peak is typically seen at the first harmonic frequency (2$\nu$), and a weaker peak often appears at the first subharmonic (0.5$\nu$). These power spectra
resemble the earlier results for XTE J1550-564 that were reported by Cui et al. (1999).

The QPOs in the range 2.6–13.1 Hz have the following characteristics. While the source is bright, the detected QPOs have a coherence parameter, $Q = \nu/\Delta \nu$, that is in the range $3.5 < Q < 12.0$. However, as the source dims, there are infrequent detections of broad QPOs with $Q \sim 1.6$ (see Figure 1 and Table 1 of paper I: Oct 29, Nov 9, and after Nov 20). The narrow QPOs are further distinguished by their high amplitudes. In particular, the individual observations between September 22 and October 13 generally yield rms amplitudes of 8-14 % of the mean count rate. Thus the X-ray luminosity, which is $\sim 1.5 \times 10^{38}(d/6\text{kpc})^2 \text{erg s}^{-1}$ (paper I), is modulated at 3–6 Hz with a crest-to-trough ratio as high as 1.5. Previously, only the microquasar GRS1915+105 has shown QPOs with such a large amplitude and a high luminosity (Morgan, Remillard, & Greiner 1997). These QPOs place significant constraints on physical models designed to explain the power-law spectrum in accreting black hole systems (e.g. Molteni, Sponholz, & Chakrabarti 1996; Titarchuk, Lapidus, & Muslimov 1998). Further analyses of these QPOs will be presented in a later publication.

While XTE J1550-564 is still in a bright state, the general shape of the power spectrum diverges from the norm on September 19 and during October 20–29. There is less power at low frequencies, and the continuum can be very roughly described as a single power law with index between 0.5 and 1.0. More importantly, these observations reveal an additional QPO near 185 Hz. This high frequency QPO is strongest in panels b and h of Figure 1. These QPOs are shown more clearly, along with the profile fits, in the left panels of Figure 2. The detections are significant at the level of 6–7 $\sigma$, and the central frequencies are located at $184 \pm 6$ and $186 \pm 7$ Hz, respectively.

Power spectra and QPO fits in two different energy bands are shown for the same two observations in Figure 3, with fit parameters given in Table 1. The uncertainty (1 $\sigma$) in
each parameter is calculated while fixing the other parameters at their best-fit value. To investigate whether this method underestimates the uncertainty, we plotted the surface contours of the chi-square statistic for each pair of QPO parameters in the 2–30 keV fits reported in Table 1. The asymmetries in these contours have only minor significance, and they imply that the multi-parameter uncertainties would be larger than the given ones by only 2–10%. For the QPO fits in the individual energy bands, where the statistics are less reliable, the centroid frequency and width were fixed at the values determined from the corresponding 2–30 keV fit. As shown in Table 1, we are able to measure the QPO amplitude independently at 2–6 keV and 6–12 keV, and there is clearly an increase in the QPO amplitude with photon energy. In addition, there is a weak indication that this trend continues into the 12–30 keV band. These results for XTE J1550-564 are qualitatively consistent with the increasing amplitude with energy seen in the 67 Hz QPO of GRS 1915+105 (Morgan, Remillard, & Greiner 1997). Thus, the fast X-ray oscillations in black hole candidates are intimately tied to the hard X-ray component in the energy spectrum.

Weaker high-frequency QPOs are seen during the days following each QPO detection at 185 Hz. The QPO fits for September 21a,b and October 24-29 are shown in the right panels of Figure 2, and the fit parameters are included in Table 1. The detections are significant at the level of 4–5 $\sigma$, and these QPOs are centered at 161 ± 7 Hz and 238 ± 18 Hz, respectively. These frequencies are inconsistent with 185 Hz at a confidence level $\sim 3\sigma$. On the other hand the derived $Q$ values and the amplitudes per energy band are consistent with the results for the stronger QPOs at 185 Hz. We must conclude that the fast QPO in XTE J1550-564 shows significant variations in frequency, the first such evidence among the three black hole candidates that display high frequency QPOs. At the 90% confidence level, the high frequency QPO in XTE J1550-564 must vary by $\sim \pm 10\%$ to be consistent with these observations. We further note that while this paper was under review and as the X-ray outburst of XTE J1550-564 continued, there were reports of even larger variations
in frequency, as a QPO appeared at 284 Hz and then settled back to 182 Hz (Homan, Wijnands, & van der Klis 1999; Remillard et al. 1999a).

4. Discussion

Spectral analyses of these 60 RXTE observations (paper I) were made using the standard model composed of a disk blackbody plus a power-law component. The results characterize the spectral evolution of XTE J1550-564 through the peak and initial decay phases of the outburst. The September 19 detection of the QPO at 184 Hz is coincident with a huge (6.8 Crab) X-ray flare that lasted between one and two days. On the other hand, the October 20-23 detection occurs during a very minor increase in intensity (∼1.5 Crab; note the small arrows in Fig. 1 of paper I). Thus intensity is a poor diagnostic of the conditions that produce the fast QPO. Far more useful indicators are the color temperature ($T_{\text{col}}$) and normalization of the disk component, which is proportional to the square of the color radius ($R_{\text{col}}$). The data in columns 8 & 9 of Table 1 in paper I show that all of the fast QPOs occur when the color temperature is relatively high ($T_{\text{col}} \gtrsim 0.84$ keV), while the disk color radius (scaled to 6 kpc with a pole-on view) is relatively small (< 40 km). We further note that the power law component contributes more than half of the total X-ray luminosity during all of our observations that occur before October 29. This entire scenario, i.e. the detection of fast QPOs when the inner disk appears small and hot while the hard X-ray power law is very strong, is the same suite of conditions that accompanied the 300 Hz QPO in GRO J1655-40 (Remillard et al. 1999b; Sobczak et al. 1999a). Furthermore, the rms amplitude of the fast QPO in XTE J1550-564 (∼ 1%) and its broad profile ($Q \sim 3.5$) are also very similar to the values derived for the 300 Hz QPO seen in GRO J1655-40.

As noted in the previous studies of fast QPOs in black hole candidates, it is natural to hypothesize that these msec timing signatures in the emission from very hot material
represent a fundamental timescale of the inner disk. However the cause of this QPO appears to involve both the disk and power-law components, since the onset of the QPO is related to the temperature of the disk, while the energy dependence of the QPO amplitude implies that the oscillation is tied to the power-law component.

Two different physical models have been advanced for these high-frequency QPOs, and both are effects of general relativity that depend on the mass and spin of the black hole. In the case of “Lense-Thirring” precession, or the “frame-dragging” model, vertical structure in the inner disk gives rise to a relativistic precession, and the precession frequency could impose a timing signature on the X-ray emission (Stella & Vietri 1998; Cui, Zhang, & Chen 1998; Merloni et al. 1998). Merloni et al. (1998) have shown that fast precession ($\nu > 10$ Hz) signifies a rapidly rotating black hole with spin parameter $a > 0.5$. A change in the precession frequency might correspond to a shift in the radius of peak X-ray emissivity. Computations by Markovic & Lamb (1998) indicate that some high-frequency modes of this oscillation may survive against strong damping. However, the means to initially excite these modes is unclear. Furthermore, it is unclear how precession of the inner disk would produce a QPO amplitude that increases with photon energy (Table 1).

An alternative model is the “diskoseismic” oscillation in which normal mode oscillations are trapped via relativistic effects in the inner disk (Perez et al. 1997; Wagoner 1998; see also Chen & Taam 1995). This model predicts oscillations in density and disk thickness that could produce observable effects in the X-ray emission. The oscillation frequency depends on the mass and spin of the black hole, as well as the radius of peak emissivity. Some of the oscillation modes also depend on the thickness of the disk, which is expected to depend on the mass accretion rate (Wagoner 1998). Therefore this model can also accomodate observed changes in the QPO frequency. Again, the mechanism by which these oscillations would reproduce the energy dependence of the QPO amplitude is not evident.
Clearly, the accumulation of numerous high-quality measurements of fast QPOs from a variety of black hole systems is a necessary step in developing a sound physical theory for this phenomenon. Guidance on interpreting the fast QPO of XTE J1550-564 may come from optical observations which may yield a determination of the mass of the black hole (paper III).

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This manuscript was prepared with the AAS \LaTeX\ macros v4.0.
Figure Legends

Fig. 1.— PCA power spectra of XTE J1550-564 in 12 sequential observation groups. The power due to counting statistics, corrected for instrument dead time, has been subtracted.

Fig. 2.— An expanded region of the PCA power spectra (2–30 keV) for the observations in which there are significant QPO detections at high frequency. Here the power density is plotted in linear units. The fits to the QPO feature and the power continuum are shown with a smooth line.

Fig. 3.— The power spectra and QPO fits are shown in two energy channels for the strongest QPO detections near 185 Hz. The central frequency and QPO width are fixed at the values determined for the sum band (2–30 keV). In each observation, the amplitude of the 185 Hz QPO increases with photon energy, as does the 13 Hz QPO seen on September 19.
<table>
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<th>Date</th>
<th>range</th>
<th>$\nu$</th>
<th>$\Delta \nu$</th>
<th>QPO amplitude</th>
<th>$\chi^2_\nu$</th>
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<td>(keV)</td>
<td>(Hz)</td>
<td>(Hz)</td>
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<td>09 18</td>
<td>2-30</td>
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<td>0.0068 (0.0010)</td>
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<td>46.7 (0.0)</td>
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<td>35.1 (11.5)</td>
<td>0.0052 (0.0012)</td>
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*The observation on September 21b yielded only the sum band at high time resolution; therefore, the analysis of the QPO amplitude in individual energy bands is limited to results from September 21a only.*
XTE J1550–564 Power Spectra

![Power Spectra Graph](image-url)