Discovery of a 65 Hz QPO and possible inner radius retreat in XTE J1550–564 during outburst decay

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1 Summary

The recurrent Soft X-ray Transient and microquasar XTE J1550-564 shows rapid X-ray variability and a hard energy spectrum very similar to that of the known Galactic black hole candidates (GBHC) (Cui et al., 1999). The power density spectra show strong aperiodic variability as well as low frequency (0.08 – 18 Hz) and high frequency (65 – 285 Hz) quasi-periodic oscillations (QPOs) (Sobczak et al., 2000; Remillard et al., 1999; Homan et al., 2001, and this work). We investigate the timing behavior of XTE J1550−564 with *RXTE* (Rossi X-ray Timing Explorer) as the source made a transition to the hard state during the decay of the 2000 outburst. We detect a high frequency QPO at 65 Hz with a fractional rms amplitude of 4.9%. This is the first time that a high frequency QPO has been detected in a transition to the hard state during outburst decay. We also observe low frequency QPOs and rich aperiodic variability and compare the timing properties with those previously observed and other GBHCs and discuss the implications for QPO models and black hole accretion.

2 Observations and Analysis

Our RXTE observations cover the decay of the 2000 outburst (Smith et al., 2000), when a transition to the hard state occurred (see Fig. 1 for the X-ray light curve). For more information about the X-ray spectrum and the radio properties of this outburst, see Tomsick, Corbel & Kaaret (2001); Corbel et al. (2001); Miller et al. (2001a,b). We used the PCA (Proportional Counter Array) power spectra to search for high frequency QPOs and study the evolution of the low frequency QPOs through the decay. For each observation, we computed the power spectra for three energy bands, 2 – 6 keV, 6 – 15 keV, and 15 – 67 keV and also for the summed band of 2 – 67 keV. Above 67 keV, the source is not significantly above the background. First, we searched for high frequency QPOs by using short 1 second segments with a Nyquist frequency of 2048 Hz using the summed energy band. Then, using 128 second time segments, we investigated the low frequency QPOs and the timing properties of the continuum up to 256 Hz.

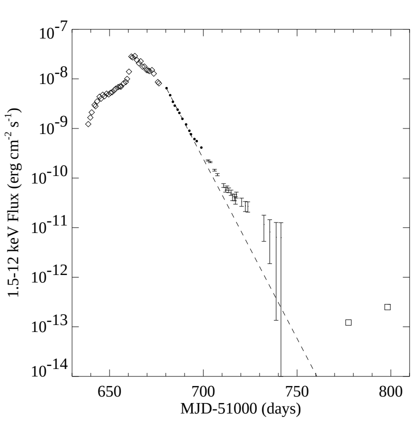

FIGURE 1: The X-ray light curve for the 2000 outburst from XTE J1550−564, including data from RXTE/ASM (diamonds), RXTE/PCA (filled circles and error bars) and *Chandra* observations (squares) (Tomsick, Corbel & Kaaret, 2001).

3 The 65 Hz QPO

Perhaps the most important result is the detection of a high frequency QPO in observation 4 at 65.0 ± 2.5 Hz (see Fig. 2c). Its rms amplitude is 4.9% in 2 – 67 keV band, and its quality value (Q) is 4.4. If we divide the light curve into three energy bands, the amplitude is 5.5 ± 1.3% for 2 – 6 keV band and 4.7 ± 1.1% for 6 – 15 keV band. The QPO is not detected in the third energy band with a 90% confidence upper limit of 4.5%. Thus, the strength of the high frequency QPO is either constant or possibly decreasing in energy. We also report the probable detection of another QPO in observation 9 at 3.9 ± 0.1 Hz, which is well above the break frequency of the FT component (see Fig. 2d). It may be related to the 65 Hz QPO and we consider the implications of this possibility below.

High frequency QPOs have been observed in five galactic BHCs ranging from 65 Hz to 450 Hz. Some are observed at a fixed frequency, and some have high frequency QPOs with variable frequency. Previous observations of XTE J1550−564 show a variable high frequency QPO with the frequency range of 100 – 285 Hz (Remillard et al., 1999; Homan et al., 2001). Thehigh frequency QPOs have rms amplitudes of $\sim 1\%$ for the whole energy band. Typically, the amplitudes increase with energy. The Q-values are between 4 and 13.

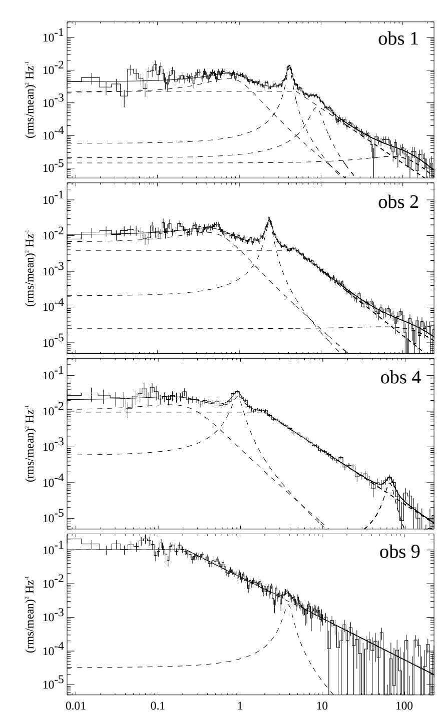

FIGURE 2: The fit to power spectra for observations 1, 2, 4 and 9. The solid line is the overall fit and the dashed lines are individual components. The full model shown in obs 1 consists of a broken power-law (hereafter flat top or FT), two narrow Lorentzians to fit the low frequency QPO and its harmonic, a broad low frequency bump (modeled by a Lorentzian) and another broad Lorentzian to fit the continuum at high frequencies. For the other observations, not all components are present at a significant level. A high frequency QPO appears in obs 4 at 65 Hz. A low frequency QPO occurs for each observation between observation 1 and 7 and the frequency of the QPO decreases (see Fig. 3). The first harmonic is statistically significant only in the first observation. The high frequency bump is necessary to fit the first four observations. The low frequency noise persists longer, and disappears after observation 8. In obs 9, we show the probable detection of a QPO at 3.9 Hz along with the FT component.

Although the properties of the 65 Hz QPO are not all typical of high frequency QPOs, the properties fit in well with trends that have been reported by other authors. For example, the soft color and the hard color are consistent with an extrapolation of the trend for XTE J1550−564 reported by Homan et al. (2001). Also the frequencies we measure for observation 4 for the low and the high frequency QPO pair are consistent with the Psaltis, Belloni & van der Klis (1999) correlation that includes the high frequency QPOs for GRO J1655−40 and previous observations of XTE J1550−564. Overall, the evidence supports an association between the 65 Hz QPO and the previously observed QPOs.

High frequencies imply that these QPOs arise close to the black hole where effects of general relativity are expected to be significant. The three models that can be applied to variable frequency QPOs are hot blobs in the inner edge of the disk (with Keplerian QPO frequency), Lense-Thirring precession of the tilted circular orbits of a spinning black hole (hereafter LT model) (Cui et al., 2000), and diskoseismic mode oscillations (Nowak & Lehr, 1998). To produce variable frequency QPOs, the first two require a change in the inner radius of the disk (Cui et al., 2000), and the last can have variable frequency if the disk thickness (h) changes as a function of radius (r). If the 65 Hz QPO in XTE J1550−564 is related to the 284 Hz QPO observed previously, then any model must explain a factor of 4 change in frequency. It was argued by Nowak & Lehr (1998) that the change in frequency due to changes in (h/r) is small, and g-mode oscillations are expected to produce low amplitude ($\sim 1\%$) QPOs. The LT mechanism, on the other hand, can account for the change in frequency. It also requires high frequency QPOs to occur during state transitions which is the case for the 65 Hz QPO. However, it is not clear how the luminosity variations can be produced by LT precession (Nowak & Lehr, 1998). Although hot blobs at the inner edge can explain the high frequency QPOs and the change in the frequency, there are reports that this model is incompatible with the spectral results (Cui et al., 2000).

If the high QPO frequencies are associated with the Keplerian or the LT time scale for the inner edge of the accretion disk, one can use the QPO frequencies to trace the radius of the inner edge of the accretion disk. We designate $\mathrm{R_{min}}$ to be the inner radius when the 284 Hz high frequency QPO was observed. If we assume that the 65 Hz QPO in observation 4 and the 3.9 Hz QPO in observation 9 are related to the 284 Hz QPO, then, for Keplerian time scales, the inner edge moves to $2.7\,\mathrm{R_{min}}$ for observation 4 and $17\,\mathrm{R_{min}}$ for observation 9. The change in radius for a LT time scale is smaller, $1.6\,\mathrm{R_{min}}$ and $4.2\,\mathrm{R_{min}}$, respectively. Esin, McClintock & Narayan (1997) developed a model consisting of an ADAF (advection-dominated accretion flow) and an optically thick outer accretion disk and used this model to explain the spectral changes seen in the BHC Nova Muscae. In the context of this model, the different spectral states can be explained by changes in the mass accretion rate and the inner edge of the optically thick accretion disk. This model predicts that the inner edge of the accretion disk moves away from the black hole during a transition to the hard state, which is consistent with the increasing of the inner radius.

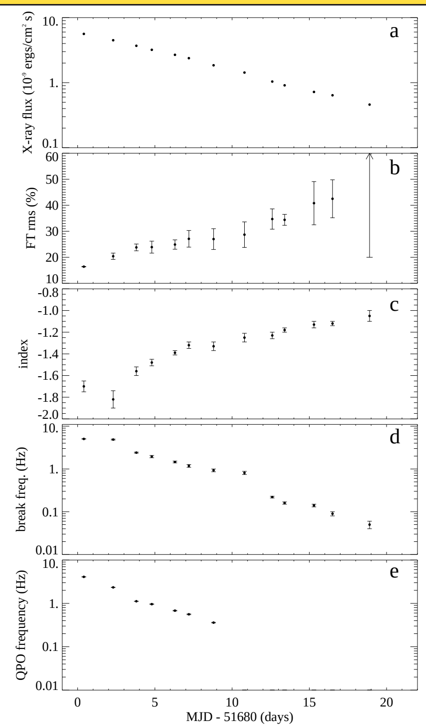

FIGURE 3: The evoultion of the fit parameters for the power spectra as the source decays. While the flux (a) decreases, the rms amplitude of the FT (b) and the index (c) increase gradually. The break frequency (d) and the QPO frequency (e) also decrease. The mirror image of these behavior was reported by Cui et al. (1999) when the source made its transition to the very high state. The temporal properties of XTE J1550−564 and BHC 4U 1630−47 are very similar during the transition to the hard state (Tomsick & Kaaret, 2000). However, for 4U 1630−47, a sharp transition was seen. For XTE J1550−564, the QPO was present and the FT rms amplitude was relatively high in our first observation. It is possible that a sharp transition might have happened before our observations began.

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