Evolution of a low frequency QPO during the 2000 outburst of XTE J1550–564

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Abstract. We follow the evolution of a low frequency QPO during the 2000 outburst of XTE J1550–564, which was found to be present in the PCA energy range (2–65 keV) in 19 of 43 observations. The frequency of the QPO varies from 0.1 Hz to 6 Hz, and appears to follow the evolution of the soft X-ray flux. If we assume the soft X-rays represent the behavior of an accretion disk, the relation indicates that this low frequency QPO is linked to the accretion disk. We show that the non-trivial relation between the QPO frequency and the soft flux may be as expected from the Accretion Ejection Instability (AEI), when the disk approaches its last stable orbit. Furthermore, the energy dependence of the QPO may indicate the presence of a hot spot rotating in the disk as predicted by the AEI.

1. AEI and QPO in microquasars

Low frequency Quasi Periodic Oscillations (LFQPO) are commonly observed in microquasars when a strong power law component is detected in their X-ray energy spectra, with a typical frequency of 0.1–10 Hz. During the Low Hard State (LHS) they have high amplitude (~ 15% rms), and during the Intermediate/Very High State (IS/VHS) they have a moderate amplitude (~ 5% rms). Their presence can be explained in the context of the Accretion Ejection Instability (AEI, [1]), which occurs in the innermost region of an accretion disk threaded by vertical magnetic field lines. The instability manifests as a spiral density wave (a hot point) rotating at 10 – 30% of the Keplerian frequency at the inner edge of the disk, producing the modulation detected as a LFQPO. One would then expect the frequency ν of the QPO to vary as ν ∝ r\(^{-3/2}\), r being the inner radius of the disk. We have shown [2] that due to general relativistic effects this relation is modified whenever the disk is close to its last stable orbit (LSO). This could explain the behavior we observed in the case of GRO J1655–40, where the relation between the QPO frequency and the disk inner radius was inverted compared to GRS 1915+105 [3], whereas the energy dependence of the QPO amplitude in GRS 1915+105 may suggest the presence of a hot point in the disk [4].

2. Spectral Overview of the 2000 outburst

XTE J1550–564 is a microquasar [5] hosting a black hole of \( M = 10.5 \pm 1.5 \ M_\odot \) [6], located at \( \sim 5.3 – 5.9 \) kpc [6]. On 2000 April 6 (MJD 51640), XTE J1550–564
became active [7] undergoing an episode of outburst. From MJD 51644–51690 the source was monitored with RXTE. We fitted the PCA+HEXTE spectra between 3 and 150 keV with a model consisting of interstellar absorption, a smeared Iron edge at $\sim 7$ keV, and a power law. A high energy cut-off is needed to fit some spectra, and a thermal component is also included in some others. The evolution of the spectral parameters is plotted in Fig. 1. Based on the spectral evolution of the source we estimate that XTE J1550–564 has transited from a low hard state (LS, photon index $< 2$) (MJD 51644–51658) into an intermediate state (IS, photon index $> 2$, thermal component) between MJD 51658 and MJD 51660. It stayed in that state until MJD 51680, and then transited back to a LS at least until the end of our study [8].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{spectral_evolution.png}
\caption{Overview of the spectral evolution of XTE J1550–564 during the 2000 outburst. Vertical lines indicate the dates of state transitions.}
\end{figure}

During the IS the small values of the color radius returned from the fits, and their relative constancy over $\sim 10$ days suggest that the inner disk is close to its LSO, in good agreement with the detection of HFQPO [9]. The disk contributes a fairly constant $2 - 50$ keV luminosity of $40 - 50\%$ during most of the IS, and after MJD 51674 the temperature starts to decrease and the disk becomes undetectable on MJD 51682. Although the late behavior of the inner radius is relatively difficult to constrain given the errors on this parameter, the disappearance of the thermal component on MJD 51682, and the observation of a 65 Hz QPO [10] favors an interpretation where as the inner edge of the disk is moving outward, its maximum temperature drops down to low values.

3. Evolution of the QPO frequency

For both epochs the evolution of the QPO frequency (Fig. 2) correlates better with the $2 - 4$ and $4 - 7$ keV band fluxes. If the evolution of the soft flux follows the behavior of the disk radius, as suggested by our spectral analysis, then the energy dependent frequency behavior favors an interpretation where the LFQPO is somehow related to the evolution of the disk. During the rising part, the energy spectra of XTE J1550–564 are dominated by the power law component. If that component characterizes an inverse Compton effect of the soft disk photons as usually assumed, the rise to outburst may indicate that the disk is approaching the black hole during the initial low state. Hence, although the frequency–flux relation is not absolutely linear (left part of Fig. 2), the increase of the frequency
with the flux still favors an association with the disk. When the disk brightens, in particular when it becomes detectable in the spectra (from MJD 51660 through MJD 51680, Fig. 1), the plot (Fig. 2 right) becomes linear, which is predicted by the AEI. The plateau and the inversion of the slope (Fig. 2) occur at high soft flux, at times where the disk reaches the highest temperatures, and contributes the most to the energy spectra. If the disk is close to the LSO during the IS, and on MJD 51674 when the QPO re-appears, the decrease of the QPO frequency after the plateau (Fig. 2) might have the same origin as the frequency-radius inversion of the correlation observed in the case of GRO J1655–40 [3], and is what one would expect from the theoretical predictions of the AEI [2]: when the disk is close to the LSO, the rotation frequency of the spiral/vortex is modified due to general relativistic effects. As the disk is moving outward (decaying soft luminosity, and no detection of the thermal component during the final LS), the frequency of QPO decreases as expected when relativistic effects are negligible.

Figure 2. Evolution of the QPO frequency with the source flux in different energy ranges during both the rise (left) and the decline (right) of the outburst.

4. Energy dependence of the LFQPO

The energy dependence of the QPO amplitude (Fig. 3 left) suggests a strong coupling between the Compton medium and the modulation, since the amplitude is high (in particular at low energies) when the source spectrum shows a strong power law (LS), and vice versa. If we assume the power-law flux is modulated and the soft component is un-modulated (i.e. the flux from the soft component does not contain the QPO), the flattening of the QPO spectrum at low energies (Fig. 3) may come from the dilution of the power law by the soft component flux. However when we look at the QPO spectra (Fig. 3 right), where we plotted the modulated flux as a function of the energy channel, and superimposed the power law returned from the spectral fits (i.e. with the same spectral index), it appears that during the LS there is a slight excess at intermediate energies, whereas during the IS there is a flattening in the soft X-rays. Our observations may suggest that the QPO originates from an independent medium, dynamically linked to the disk. The QPO flux at high energies would then simply reflect the inverse Compton reprocessing of soft photons on the coronal electrons, while at lower energy this additional component would explain the observed spectra.

The addition of a 1.3 keV blackbody (not shown) may allow a better fit to
the spectra, at least during the initial LS [1]. This would be consistent with the theoretical predictions of the AEI. In that case, the QPO would be the direct signature of the instability as it forms shocks (spiral) and warms locally the disk, giving birth to a local hot point a bit warmer than the entire disk in its average.

5. Conclusion

We propose that theoretical predictions of the AEI model match many observational constraints, starting with the non trivial evolution of the QPO frequency vs. the (soft) flux, and by extension the disk radius. We show that a hot point rotating in the disk, which is an expected signature of the AEI, is compatible both with the frequency evolution of the flux modulation and the energy spectrum of the QPO.

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References

1. Tagger M. & Pellat R., 1999, A& A, 349, 1003.
2. Varnière P., Rodriguez J., Tagger M., 2002, A&A, 387, 497.
3. Rodriguez J., Varnière P., Tagger M., Durouchoux P., 2002, A&A, 387, 487.
4. Rodriguez J., Durouchoux P., Mirabel F., Ueda Y., Tagger M., Yamaoka K., 2002, A&A, 386, 271.
5. Hannikainen D., Campbell-Wilson D., Hunstead R., McIntyre V., Lovell J., Reynolds J., Tzioumis T., Wu K., 2001, Ap&SS, 276, 45.
6. Orosz J.A., Groot P.J., van der Klis M., McClintock J.E., Garcia M.R., Zhao P., Jain R.K., Bailyn C.D., Remillard R.A., 2002, ApJ, 568, 845.
7. Smith D.A., Levine A.M., Remillard R., Fox D., Schaefer R., RXTE/ASM Team, 2000, IAU Circ. 7394.
8. Rodriguez J., Corbel S., Kalemci E., Tom sick J.A., Proceedings of the XXII Moriond Astrophysics Meeting "The Gamma Ray Universe", March 2002, [astro-ph/0205341].
9. Miller J.M., Wijnands R., Homan J., Belloni T., Pooley D., Corbel S., Kouveliotou C., van der Klis M., Lewin H.G., 2001, ApJ, 563, 928.
10. Kalemci E., Tom sick J.A., Rothschild R.E., Pottschmidt K., Kaaret P., 2001, ApJ, 563, 230.
11. Rodriguez J., Corbel S., Kalemci E., Tom sick J.A., Tagger M., 2002 Submitted to ApJ.