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LETTER TO THE EDITOR

Evolution of the quasi-periodic oscillation frequency in GRO J1655-40 – Implications for accretion disk dynamics

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ABSTRACT

Context. Low and intermediate frequency quasi-periodic oscillations (QPOs) are thought to be due to oscillations of Comptonizing regions or hot blobs embedded in Keplerian disks. Any movement of these perturbations is expected systematically to change the QPO frequency.
Aims. Our goal is to find systems where such a systematic drifts have been observed. We also try to find the real cause of such drifts and whether they shed some light on the accretion disk dynamics.
Methods. Using archival data of the recent outburst of GRO J1655-40, we report the presence of such systematic drifts not only during the rising phase from the 25th of February 2005 to the 12th March 2005, when the QPO frequency monotonically increased from 82 mHz to 17.78 Hz but also in the decline phase from the 15th September 2005 to the 5th of October 2005, when the QPO frequency decreased from 13.14 Hz to 34 mHz.
Results. We fitted the frequency drifts with the propagatory oscillating shock solution. In the shock-oscillation solution, the frequency is inversely proportional to the infall time scale from the shock location. We obtained the shock location and strength through such a fit.
Conclusions. The astonishing smoothness of the variation of the QPO frequency over a period of weeks directly supports the view that it may due to the drift of an oscillating shock rather than the movements of a blob inside a differentially rotating disk.

Key words. accretion, accretion disks – black hole physics – shock waves – X-rays: binaries

1. Introduction

The galactic nano-quasar GRO J1655-40 is an interesting low mass X-ray binary (LMXB) with a primary mass $M = 7.02 \pm 0.22\ M_{\odot}$ (Orosz & Bailyn 1997) and the companion star mass $= 2.3\ M_{\odot}$ located at a distance of $D = 3.2 \pm 0.2$ kpc (Hjellming & Rupen 1995). The disk has an approximate inclination angle of $\theta = 69.5^{\circ} \pm 0.1^{\circ}$ (Orosz & Bailyn 1997) to the line of sight. In the last week of February 2005 it became X-ray active (see Shaposhnikov et al. 2007, and references therein) and remained so for the next 260 days before returning to the hard state. In this Letter, we thoroughly analyse the data of the first two weeks of the very initial stage (rising phase) and the last three weeks of the final stage (decline phase) of the 2005 outburst. We clearly observe very smooth day to day variation of the QPO frequency in these two phases. We propose that a satisfactory explanation of this behavior can be obtained if we assume that an oscillating shock which is sweeping inward through the disk in the rising phase and outward in declining phase is responsible for the QPO. In the next section, we briefly present an overview of QPOs observed in the black hole candidates. In Sect. 3, we present the shock oscillation solution for the generation of QPOs. In Sect. 4, we present the observational results in detail and show our model fit of the QPO frequencies from day to day. We interpret the results and extract the shock parameters. In Sect. 5, we give a coherent description of the rising and the declining phases of the outburst.

2. Low and intermediate frequency QPOs in black hole candidates

Observations of low and intermediate frequency quasi-periodic oscillations (QPOs) in black hole candidates have been reported quite extensively in the literature. One satisfactory model shows that the oscillation of X-ray intensity is actually due to the oscillation of the post-shock (Comptonizing) region (Molteni et al. 1996, hereafter MSC96; Chakrabarti & Manickam 2000, hereafter CM00). Perturbations inside a Keplerian disk also have been assumed to be the cause of low-frequency QPO also (e.g., Trudolyubov et al. 1999; see, Swank 2001, for a review). The numerical simulations of low-angular momentum accretion flows including the thermal cooling effects (MSC96; Chakrabarti et al. 2004, hereafter CAM04) or dynamical cooling (through outflows, e.g., Ryu et al. 1997) show clearly that the shocks oscillated with frequencies similar to the observed QPO frequencies. Not only were the shock locations found to be a function of the cooling rate (MSC96), they were found to propagate when viscous effects are turned on (Chakrabarti & Molteni 1995).

3. The properties of low and intermediate frequency QPOs from shock oscillations

It has been argued in the past that steady, propagating and oscillating shocks can form in a low angular momentum flow (e.g., CAM04 and references therein). In the shock oscillation solution

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(MSC96, CM00; CAM04) of QPOs, the oscillations take place at a frequency inverse to the infall time in the post-shock region (i.e., the region between the shock at $r = r_{\rm s}$ and the horizon). In a shock-free low angular momentum flow, this infall time is $t_{\rm infall} \sim r_{\rm s}/v = r_{\rm s}(r_{\rm s}-1)^{1/2}$, where $v = 1/(r_{\rm s}-1)^{1/2}$ is the free-fall velocity in a pseudo-Newtonian potential (Paczynskí & Wiita 1980) $\phi_{\rm PN} = -1/(r_{\rm s}-1)$. Here, distance, velocity and time are measured in units of the Schwarzschild radius $r_{\rm g} = 2GM/c^2$, the velocity of light c and $r_{\rm g}/c$ respectively and where, G and M are the universal constant and the mass of the black hole. However, in the presence of a significant angular momentum capable of producing centrifugal pressure supported shocks around a black hole, the velocity is reduced by a factor of R, the compression ratio $R = \rho_-/\rho_+$, where, ρ_- and ρ_+ are the densities in the pre-shock and the post-shock flows, because of the continuity equation $\rho_- v_- = \rho_+ v_+$ across a thin shock.

In the presence of a shock, the infall time in the post-shock region is therefore given by

$$t_{\rm infall} \sim r_{\rm s}/v_+ \sim R r_{\rm s}(r_{\rm s}-1)^{1/2} \quad (1)$$

(CM00; Chakrabarti et al. 2005). Of course, to trigger the oscillation, the accretion rate should be such that the cooling time scale roughly match the infall time scale (MSC96). Thus, the instantaneous QPO frequency $\nu_{\rm QPO}$ (in s^{-1}) is expected to be

$$\nu_{\rm QPO} = \nu_{\rm s0}/t_{\rm infall} = \nu_{\rm s0}/\left[R r_{\rm s}(r_{\rm s}-1)^{1/2}\right]. \quad (2)$$

Here, $\nu_{\rm s0} = c/r_{\rm g} = c^3/2GM$ is the inverse of the light crossing time of the black hole of mass M in s^{-1} and c is the velocity of light. In a drifting shock scenario, $r_{\rm s} = r_{\rm s}(t)$ is the time-dependent shock location given by

$$r_{\rm s}(t) = r_{\rm s0} \pm v_0 t/r_{\rm g}. \quad (3)$$

Here, $r_{\rm s0}$ is the shock location when t is zero and v_0 is the shock velocity (in cgs units) in the laboratory frame. The positive sign in the second term is to be used for an outgoing shock in the declining phase and the negative sign is to be used for the in-falling shock in the rising phase. Here, t is measured in seconds from the first detection of the QPO.

The physical reason for the oscillation of shocks appears to be a "not-so-sharp" resonance between the cooling time scale in the post-shock region and the infall time scale (MSC96) or the absence of a steady state solution (Ryu et al. 1997). In both the cases, the QPO frequency directly gives an estimate of the shock location (Eq. (1)). The observed rise of the QPO frequencies with luminosity (e.g., Shaposhnikov & Titarchuk 2006, hereafter ST06) is explained easily in this model since an enhancement of the accretion rate increases the local density and thus the cooling rate. The resulting drop of the post-shock pressure reduces the shock location and increases the oscillation frequency. In CM00 and Rao et al. (2000) it was shown that QPOs from the higher energy Comptonized photons, thought to be from the post-shock region, (Chakrabarti & Titarchuk 1995), have a higher Q value. The latter model requires two components, one Keplerian and the other having an angular momentum lower than the Keplerian (referred to hereafter as sub-Keplerian), and explains a wide variety of observations of black hole candidates (Smith et al. 2002, 2001, 2007). As the shocks are the natural solutions to this sub-Keplerian component, explanation of QPOs from shocks is justified. When the Rankine-Hugoniot relation is not exactly satisfied at the shock or the viscous transport rate of the angular momentum is different on both sides, the mean shock location would drift slowly due to a difference in pressure on both sides. In the rising phase of the outburst, a combination of the ram pressure of the incoming flow and rapid cooling in the post-shock region (which lowers the thermal pressure) pushes the oscillating shock inward. In the decline phase, the Keplerian disk itself recedes outward creating a lower thermal pressure in the post-shock region. In this case, the shock drifts outward.

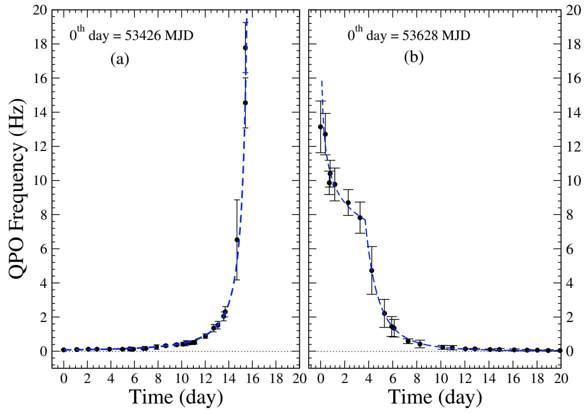

Fig. 1. Variation of QPO frequency with time (in day) **a)** of the rising phase and **b)** of the declining phase. Error bars are FWHM of fitted Lorentzian curves in the power density spectrum. The dotted curves are the solutions from oscillating and propagating shocks. While in **a)** the shock appears to be drifting at a constant speed towards the black hole, in **b)** the shock initially moves very slowly and then extends at a roughly constant acceleration. According to the fitted solution, the shock wave goes behind the horizon on the 16.14th day, about 15 h after the last observed QPO.

4. Observational results and analysis

We concentrate on the publicly available data of 51 observational IDs (corresponding to observations of a total of 36 days) of GRO J1655-40 acquired with the RXTE Proportional Counter Array (PCA; Jahoda et al. 1996). Out of these IDs, 27 are of the rising phase (from MJD 53 426 to MJD 53 441) and 24 are of declining phase (from MJD 53 628 to MJD 53 648). We extracted the light curves (LC), the PDS and the energy spectra from the good detector unit PCU2 which also happens to be the best-calibrated. We used the FTOOLS software package version 6.1.1 and the XSPEC version 12.3.0. For the timing analysis (LC and PDS), we used the Science Data of the Normal mode (*B_8ms_16A_0_35_H*) and the Event mode (*E_125us_64M_0_1s*, *E_62us_32M_36_1s*). To extract LC from Event mode data files, we used "sefilter" task and for the normal mode data files, we used "saextrct" task. For the energy spectral analysis, the "Standard2f" Science Data of PCA was used. For PCA background estimation purpose the "pcabackest" task was used while to generate the response files the "pcarsp" task was utilized. For the rebinning of the "pha" files created by the "saextrct" task, we used the "rbnpha" task. For all the analysis, we kept the hydrogen column density ($N_{\rm H}$) fixed at 7.5×10^{21} atoms cm^{-2} and the systematics at 0.01.

Figures 1a, b show the variation of the QPO frequencies in (a) the rising and (b) the declining phases of the outburst. The full widths at half maxima of the fitted QPOs have been used as the error bars. In the rising phase (a), the 0th day starts on MJD = 53 426. The fitted curve represents our fit with Eqs. (2), (3) which requires that the shock is launched at $r_{\rm s} = 1270$ which drifts slowly at $v_0 = 1970$ cm s^{-1}. On the 15th day after the outburst starts, the noise was high, but we could clearly observe two different QPO frequencies with a very short time interval. At the time of the last QPO detection (15.41th day) at $\nu = 17.78$ Hz, the shock was found to be located at $r \approx 59$. The strength of the shock R, which may be strong at the beginning with $R = R_0 \sim 4$ should become weaker and ideally $R \sim 1$ at the horizon $r = 1$, as it is impossible to maintain density gradient on the horizon. If for simplicity we assume the variation of the shock strength as $1/R \rightarrow 1/R_0 + \alpha t_{\rm d}^2$, where α is a very small number limited by the time in which the shock disappears (here $t_{\rm ds} \sim 15.5$ days). Thus, the upper limit of $\alpha \sim (1-1/R_0)/t_{\rm ds}^2 = 0.75/t_{\rm ds}^2 = 0.003$. We find that for a best fit, $\alpha \sim 0.001$ and the reduced $\chi^2 = 0.96$. However, the fit remains generally good ($\chi^2 = 1.71$ for $xs0 = 1245$ and $v0 = 1960$ cm/s) even with a shock of constant strength ($R = R_0$). Hence for a generally good fit the number free parameters could be assumed to be three: the shock strength, initial shock location and the shock velocity.

In the declining phase (Fig. 1b), the QPO frequency on the first day (MJD = 53 631) corresponds to launching the shock at $\sim r_{\rm s} = 40$. It evolves as $\nu_{\rm QPO} \sim t_{\rm d}^{-0.2}$. Since $\nu_{\rm QPO} \sim r_{\rm s}^{-2/3}$ (Eq. (1)), the shock was found to drift very slowly with time ($r_{\rm s} \sim t_{\rm d}^{0.13}$) until about $t_{\rm d} = 3.5$ day where the shock location was $\sim r = 59$. There is a discontinuity in the behavior at this point whose possible origin is obtained from spectral studies presented below. After that, it moves out roughly at a constant acceleration ($r_{\rm s} \sim t_{\rm d}^{2.3}$) and the QPO frequency decreases as $\nu_{\rm QPO} \sim r_{\rm s}^{-2/3} \sim t_{\rm d}^{-3.5}$. Finally, when the QPO was last detected, on $t_{\rm d} = 19.92$th day (MJD = 53 648), the shock went as far as $r_{\rm s} = 3100$ and the oscillation could not be detected any longer. The strength of the shock was kept at $R = 4$. The reduced χ^2 for the fit is given by 0.236. In Figs. 2a,b, we present the dynamic PDS where the vertical direction indicates the QPO frequency. Results of five dwells are given in both the rising and the declining phases. The grayscale has been suitably normalized so as to identify the QPO features prominently.

In order to examine how the disk was re-adjusting itself in these two phases, we studied both the timing and the spectral properties and plot the results in Fig. 3 (panels i to v) we give an idea of this by providing the PDS (left panels) and the fitted energy spectrum (right panels) of five observations. The observation IDs are: 91702-01-01-01 (11.0315th day) and 91702-01-02-00G (14.6957th day) of the rising phase and 91702-01-76-00 (0th day), 91702-01-80-00 (3.27th day) and 91702-01-81-01 (6.118th day) of the declining phase respectively. In the rising phase, the spectrum clearly becomes softer as the shock moves in and the QPO frequency increases. The softening of the spectrum with the increase in the QPO frequency has been reported by various authors (e.g., Chakrabarti et al. 2005; ST06; Shaposhnikov et al. 2007). From a theoretical point of view, MSC96 explicitly showed that increased cooling reduces the shock location and increases the QPO frequency. This was also reported by ST06 using the data of Cyg X-1. We observe that the black body (BB) component from the Keplerian disk and the Gaussian (G) components are also strengthened. The Gaussian component could be from iron lines, but due to poor resolution of RXTE this cannot be said with certainty. In the declining phase, as the QPO frequency decreases, all three of the black body (BB), the power-law (PL) component and an additional Comptonization component (using Comptonization through the Sunyaev-Titarchuk or CST model) from the region decreases. Interestingly, this additional cooler CST component with a cut-off was required only before the discontinuity observed on 3.5th day in the outgoing phase, signifying that perhaps there were two sources of

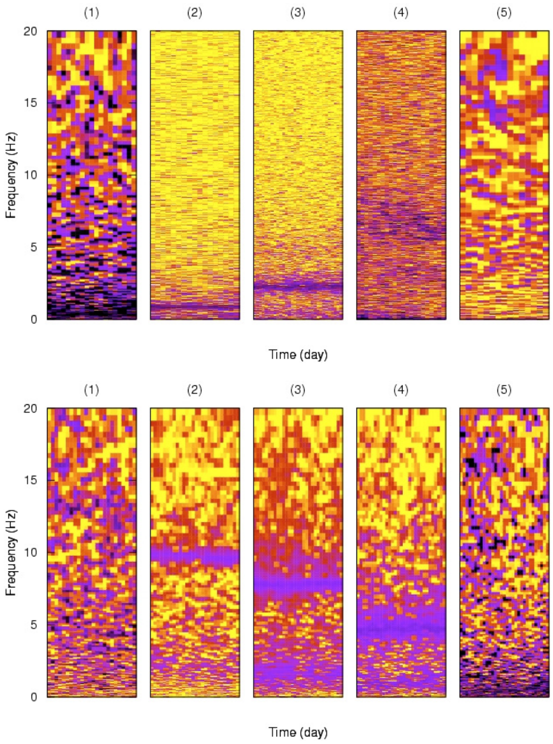

Fig. 2. a) Dynamic power density spectra over five days in the rising phase. (1) Obs. ID = 91404-01-01-01, QPO = 0.382 Hz; (2) Obs. ID = 91702-01-01-03, QPO = 0.886 Hz; (3) Obs. ID = 90704-04-01-00, QPO = 2.3130 Hz; (4) Obs. ID = 91702-01-02-00, QPO = 3.45 and 6.522 Hz with a break frequency at 0.78 Hz and (5) Obs. ID = 91702-01-02-01, QPO =1 4.54 and 17.78 Hz. **b)** Dynamic power density spectra over five days in the decline phase. (1) Obs. ID = 91702-01-76-00, QPO = 13.14 Hz; (2) Obs. ID =9 1702-01-79-01, QPO = 9.77 Hz; (3) Obs. ID = 91702-01-80-00, QPO = 7.823 and 15.2 Hz with a break frequency at 1.32 Hz; (4) Obs. ID = 91702-01-80-01, QPO = 4.732 Hz with a break frequency = 0.86 Hz; (5) Obs. ID = 91702-01-82-00, QPO = 0.423 Hz.

X-rays: one (PL) from the post-shock region and the other (CST) from the outflow region. Ultimately, after the discontinuity, only a weak power-law component remains which is emitted from a hot tenuous sub-Keplerian flow. This is all that remains after the outburst is over. We interpret this observation to be associated with a possible change in the flow behavior at $r \sim 59$: either the shock is propagating from the disk region to the outflow region or the shock is moving away from the black hole due to the low pressure in the emptied disk. We also note that the disk component which was becoming stronger in the rising phase is absent in the late declining phase, indicating that the Keplerian component disappears soon after the outburst is over.

5. Discussions and concluding remarks

In this Letter, we show that during the rising phase of the outburst of GRO J1655-40, the QPO frequency increases very slowly in the first few days and then rapidly increases to about 18 Hz before it disappears altogether. Our slowly drifting shock oscillation solution explains this variation very accurately. Our estimation suggests that the shock was at 1270 Schwarzschild radii when the first observation of QPO was made and it went to $r = 59$ Schwarzschild radii when it was last observed. Within 15 h of this, the shock front went inside the horizon and thus when the observation was made on the next day, the QPO was

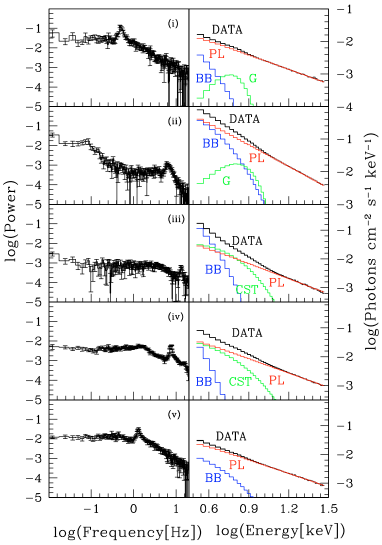

Fig. 3. Power density spectrum (*left panel*) and energy spectral index (*right panel*) of the rising phase (i and ii) and the declining phase (iii–v). The QPO frequencies are (i) 0.513 Hz (0.632); (ii) 3.45 and 6.522 Hz (0.441); (iii) 13.14 Hz (0.848); (iv) 7.823 Hz (1.14) and (v) 1.347 Hz (1.29) respectively. Numbers next to frequencies are the reduced χ^2 values. The components used for fitting the energy spectra are marked: "DATA" for total fit, "BB" for black body, "G" for Gaussian, "CST" for Comptonization using the Sunyaev-Titarchuk (1980) model with an exponential cutoff, "PL" for a power-law component without a cut-off.

absent. The inward drift velocity of the shock was slow, only about 20 m s^{-1}. As the shock proceeds close to the black hole, the Keplerian disk follows the shock and the energy spectrum gradually became softer with the black body component becoming stronger each day. Thus the whole scenario is consistent with our theoretical understanding (MSC96) that this drift is due to the reduction of the post-shock pressure by the increased cooling effects in addition to the higher upstream ram pressure. Both MSC96 and CAM04 computed the cooling timescale using bremsstrahlung and Comptonization respectively and showed that oscillations occur when the infall time scale is comparable to these coolings in super-massive and staller mass black holes respectively. As a consistency check, one could also use the fitted spectrum to compute the electron temperature and calculate the cooling time scale from $E_{\rm th}/\dot{E}$ where, $E_{\rm th}$ is the thermal energy content of the electrons and $\dot{E}$ is the rate of cooling due to Comptonization. However, $E_{\rm th}$ depends on the accretion rate and electron temperature and $\dot{E}$ depends on the enhancement factor (Dermar et al. 1991). However, the PCA data from 3–25 keV does not allow one to compute the these unknowns unambiguously.

In the decline phase, the QPO frequency was found to be decreasing monotonically. This means that an oscillating shock is propagating outwards. The nature of the reduction of QPO frequency is very curious. For the first ~3.5 days, the shock location did not change very much, from ~40 to ~59 or so, as if it was stalling. In this phase an additional cooler Comptonized component was required. After this, the shock suddenly moved away with almost constant acceleration for another 16 days before the QPO disappeared completely. The spectrum remained hard and the intensity decreased monotonically. Towards the end, the spectrum is dominated only by the power-law component. We conjecture that in the first ~3.5 days the shock remained inside the disk drifting slowly outward, perhaps due to interaction of the receding shock with the still incoming Keplerian flow. After that, the receding Keplerian disk created a vacuum in the system and accelerated the shock wave outward. This is indicated by almost square-law behavior of the shock location.

In the two component advective flow model that we are using, the shock forms in the sub-Keplerian component since a Keplerian flow is subsonic and cannot have a shock. At the onset of the rising phase of the outburst, only the sub-Keplerian flow rate increases rapidly since it is almost freely falling. The shocks we consider may have actually formed farther out (than $1270 r_{\rm g}$, for example) we could detect them only when the rms value of the QPO is high enough. Similarly, when the shock comes closer to the black hole horizon, the noise also rises and QPOs may not be detectable as well.

The observational result we described here is unique in the sense that we are able to connect the QPO frequency of one observation with that of the next by a simple analytical formalism. To our knowledge no competing model exists which uses a true solution of the flow, such as shocks in our case, to explain such a behavior. In any case, even if the QPOs were generated by certain non-axisymmetric feature (such as a blob), it is impossible that it will survive beyond a few orbital time-scales. Furthermore, the smooth decrease of QPO frequency requires that the blob moves outwards through a differentially rotating disk for some weeks, odds of which is insignificant. If our explanation of the propagation of shocks is correct, then this outburst shows convincingly how a shock wave smoothly disappears behind the horizon after ~16 days of its initial detection. Thus, such an observation would be unlikely in neutron star candidates. Our interpretation is generic and other outburst sources should also show such systematic drifts. A discussion of other similar sources will be dealt with in future.

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