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Propagating oscillatory shock model for QPOs in GRO J1655-40 during the March 2005 outburst

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Abstract : GRO J1655-40, a well known black hole candidate, showed renewed X-ray activity in March 2005 after being dormant for almost eight years. It showed very prominent quasi-periodic oscillations (QPO). We analysed the data of two observations in this *Rapid Communication*, one taken on March 2nd, 2005 and the other taken on the March 11th, 2005. On March 2nd, 2005, the shock was weak and the QPO was seen in roughly all energies. On March 11th, 2005, the power density spectra showed that quasi-periodic oscillations (QPOs) were exhibited in harder X-rays. On the first day, the QPO was seen at 0.13 Hz and on the second day, the QPO was seen at ~6.5 Hz with a spectral break at ~0.1 Hz. We analysed the QPOs for the period 25th February 2005 to 12th of March, 2005 and showed that the frequency of QPO increased monotonically from 0.088 Hz to 15.01 Hz. This agrees well if the oscillating shock is assumed to propagate with a constant velocity. On several days, we also noticed the presence of very high frequency QPOs and for the first time, we detected QPOs in the 600 – 700 Hz range, the highest frequency range so far reported for any black hole candidate.

Keywords : Black Holes, X-ray sources, stars : individual (GRO J1655-40), shock waves.

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1. Introduction

The well known galactic microquasar GRO J1655-40, which is about 3 kpc away from us [1], and had been dormant since 1997, has suddenly come to life in March, 2005 [2]. The RXTE X-ray count has started rising on a daily basis. In this *Rapid Communication,* we shall 90428-examine its behaviour in two of the observations, one taken at the early stage of the outburst on the March 2nd, 2005 (Obs. ID 90428-01-01-09) and the other taken when the outburst is well under way on the 11th of March, 2005 (Obs. ID : 91702-01-02-00G). The shocks may be generated due to the appearance of a new wave of matter and they steepen as the shock propagates closer to the black hole. The oscillation of the shock model explains all the aspects of the quasi-periodic oscillations [3–6] and the QPO frequency is found to be generally related to the infall time $t_{if} = \frac{1}{R}\frac{1}{x_s(x_s - 1)}$, where R is the shock compression ratio ~4 and x_s is the instantaneous location of the shock. In case the shock propagates towards the black hole, the frequency is expected to rise monotonically. This would be of interest if we can show that (a) the QPOs are indeed from shock oscillations and (b) shock frequency increases monotonically according to the shock propagation model. In Chakrabarti and Manickam [5] and Rao *et al* [6], it was shown that another black hole candidate GRS 1915 +105 had exhibited QPOs where shock oscillation model was found to be valid. During the 1996/1997 outburst of GRO J1655-40, Remillard *et al* [7] also reported energy dependence of high frequency QPOs, although no satisfactory model was discussed which could explain these behaviours. In this communication, we also report the possible presence of a very high frequency QPO at ~600 Hz, the highest known QPO for any black hole candidate to date.

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In the next Section, we present a brief introduction of the accretion processes around black holes. In Section 3, we present the results of the observations. We show that the nature of the hardness ratios have changed qualitatively and quantitatively in between these two days. We also plot the power density spectra of the photons at different energy. In Section 4, we make concluding remarks.

2. Brief description of the black hole accretion

Detailed descriptions of black hole accretion are given in several review articles and in several recent articles [8–10] and we do not repeat them here. Briefly speaking, a black hole accretion is necessarily sub-Keplerian, *i.e.*, the specific angular momentum of matter is less than the Keplerian value because of the fact that the flow must satisfy the inner boundary condition on the horizon where matter must be supersonic and its velocity must be equal to the velocity of light. Given that matter moves very rapidly, the infall time becomes very low compared to any other time scale, specifically, the viscous time scale in which angular momentum of matter is transported outward. Because angular momentum remains virtually constant, the centrifugal barrier becomes so strong that matter almost halts at the barrier. This is known as the shock wave at which matter undergoes a super-sonic to sub-sonic transition. The location of the shock may form anywhere between ~10 to ~1000r_g (henceforth, our unit of distance will be the Schwarzschild radius of the central black hole : $r_g = 2GM/c^2$, where G and c are the gravitational constant and the velocity of light respectively and M is the mass of the black hole) depending on the specific angular momentum of the flow, with a typical value of around 10 – 15. A standing shock forms where the Rankine-Hugoniot conditions are satisfied. When the conditions are not satisfied, the shock starts oscillating depending on the exact parameters of the flow.

It has been argued in Molteni, Sponholz and Chakrabarti [3] that the oscillating shocks will cause QPOs in X-rays. In Chakrabarti and Manickam [5] and Rao *et al* [6], it was shown that the microquasar GRS 1915+105 indeed exhibited QPOs which are correctly modeled by shock-oscillations. They also showed that while the soft X-rays do not show much oscillations, hard X-rays do. This is because the post-shock region (otherwise known as the CENBOL – CENtrifugal pressure dominated BOundary Layer) produces hard X-rays by inverse-Comptonizing the intercepted soft X-rays emitted from the pre-shock flow and also participates in oscillations more strongly than the pre-shock region [11].

3. Results and discussions

We analysed the data of the recent outburst using the PUBLIC data of RXTE satellite. We use the observation IDs 90428-01-01-09 (March 2nd, 2005) and 91702-01-02-00G (March 11th, 2005). We used only PCU2 as other PCUs are not very stable. The data analysis techniques have been reported elsewhere [5,6,9,10]. In order to quantify the nature of the spectra, it is customary to plot the hardness ratios. We extracted the photon counts in three bins with Channel numbers 0 – 6 (0 – 2.87 keV), 7 – 23 (2.87 – 9.81 keV) and 24 – 249 (9.81 – 117 keV) respectively and saved then in 1s time bins. The ratios R_1 = *Channel*(7 – 23)/*Channel*(0 – 6) and R_2 = *Channel*(7 – 23)/*Channel*(24 – 249) will then give an idea about how the spectrum is changing with time. In Figure 1, we show the variation of R_2 as a function of R_1 for both the observations (marked). We note that though the observations were only 10 days apart, the hardness ratios behave completely differently. On March 2nd, the (R_1, R_2) is centered around ~(10, 1) indicating that the spectra was dominated by both the ~3 – 10 keV photons and by > 10 keV photons. Low energy (< 3 keV) photons were not significantly present. On the other hand, on March 11th, 2005, we see that the (R_1, R_2) is centered around ~ (9, 5.5) indicating that the spectra is dominated *only* by 3 – 10 keV photons and neither the lowest, and nor the highest energy photons were significantly present.

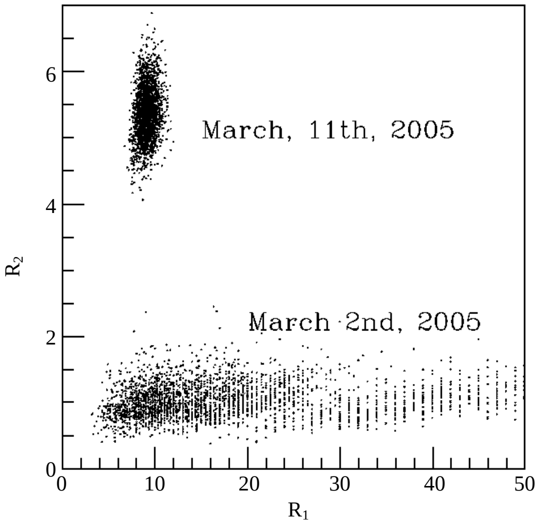

Figure 1. Plots of hardness ratios R_1 = *Channel*(7 – 23)/*Channel*(0 – 6) *vs.* R_2 = *Channel*(7 – 23)/*Channel*(24 – 249) of 1s bin lightcurves on the (a) March 2nd, 2005 and on (b), March 11th, 2005, respectively. In (a), the intermediate (2.87 – 9.81) and high (> 9.81) energy photons are dominant while in (b), only intermediate (2.87 – 9.81) energy photons are dominant.

We now show that not only the hardness ratios, but the timing characteristics of the spectra are very much different. In Figure 2, we show the power density spectra (PDS) in these three energy bins. In the uppermost panel, which is drawn for 0 – 2.87 keV photons, there is a very weak and noisy QPO feature at ~0.13 Hz. In the middle panel, this feature is more prominent but the power is lower. The QPO frequency is at 0.13 Hz with an width 0.03 Hz. In the lower panel, the QPO feature is still present and possibly sharper, but the data is noisy and the power is definitely low. This is to be contrasted with the energy dependence of the high frequency QPO seen on the March 11th, in which the QPO frequency is higher (~6.5 Hz) and the power increased progressively at higher energy channels, thus providing a convincing proof that the harder photons emitted from the post-shock region are participating in the QPO process.

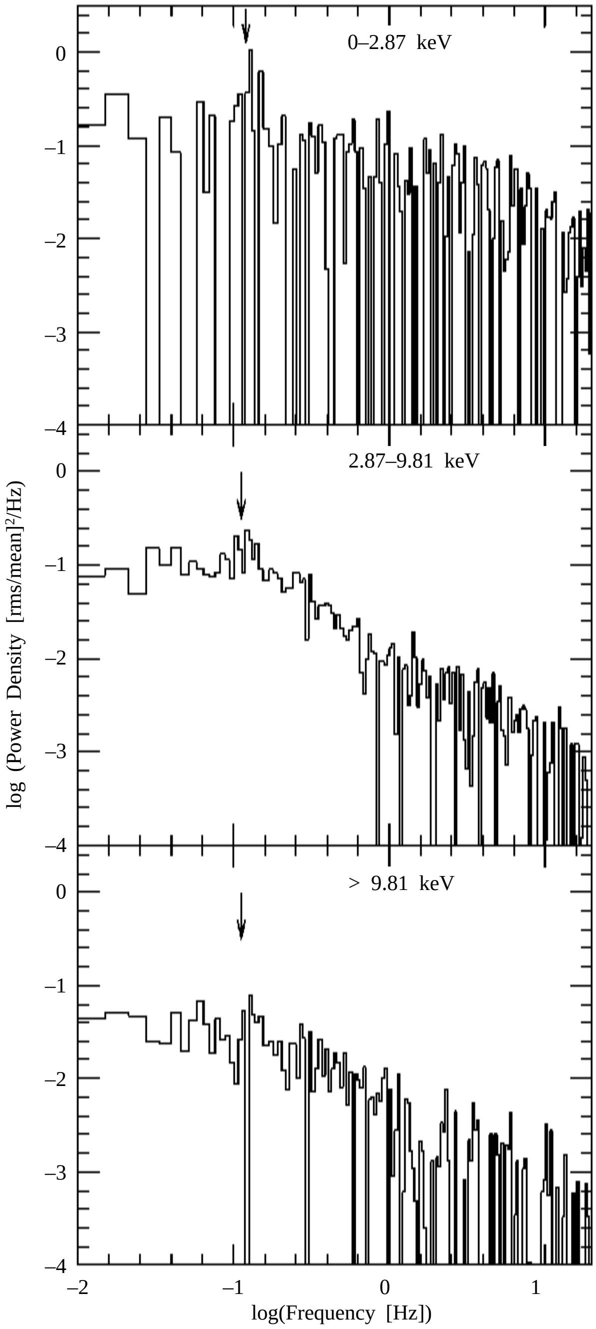

Figure 2. Power density spectra (PDS) of the (a) low (0 – 2.87 keV), (b) intermediate (2.87 – 9.81 keV) and (c) high (> 9.81 keV) photons of March 2nd, 2005 (Obs ID : 90428-01-01-09) showing that the QPOs are exhibited by higher energy photons coming from the post–shock region. In (c), the photon counts are very low and the QPO is very noisy, though sharper.

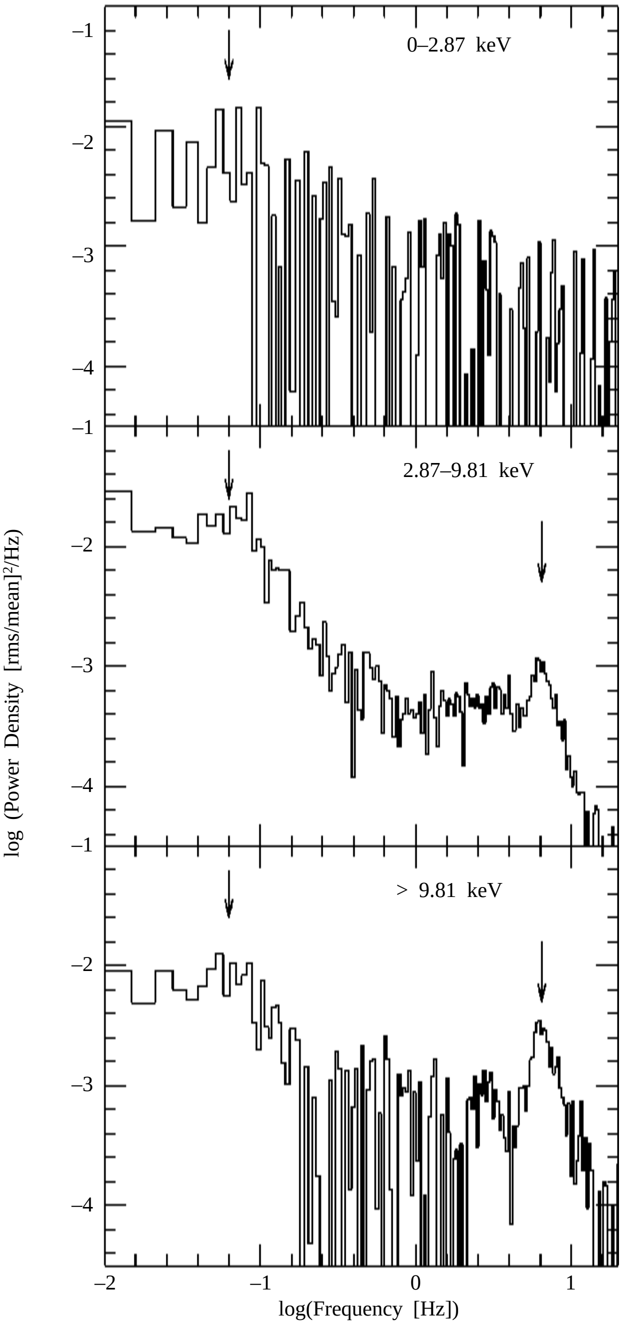

Figure 3. Power density spectra (PDS) of the (a) low (0 – 2.87keV), (b) intermediate (2.87 – 9.81keV) and (c) high (> 9.81keV) photons of March 11th, 2005 (Obs ID:91702–01–02–00G) showing that the QPOs are exhibited by higher energy photons coming from the post–shock region. The power at ν_{QPO} ~ 6.5Hz in (c) is three times more compared to that in (b).

Comparing the behaviour in Figure 2 and Figure 3, we believe that the shock was weaker originally and it steepened as the frequency rises.

In order to show the propagation of the shock, in Figure 4, we plot the daily variation of the QPO frequency between 25th of February, 2005 when the observation of significant photon count started till 12th of March, 2005 beyond which the QPO disappeared in this episode. Superposed on the plot, we presented a theoretical plot which assumed that the shock is propagating with a constant velocity ν_0. Hence, the time measured from the observation of 25/2/05 when the shock was at $x_s = x_{s0}$, is given by $t = (x_{s0} - x_s)/\upsilon_0$. The frequency of QPO is already mentioned to be $\nu_s = \frac{\beta}{x_s(x_s-1)^{1/2}}$, where, $\beta \sim 1/R \sim 0.25$ is the inverse of the shock strength R. The observed frequency $\nu_{s0} = 0.088$ at $t = 0$ directly gives $x_{s0} = 1200$ as the launching radius. The constraint on the disappearance of the QPO on the latter half of the 12th of March, 2005, (~15.6 d from the beginning of launching), gives a very slow rate of shock propagation and the velocity is $\upsilon_0 \sim 1870$ cm s^{-1}.

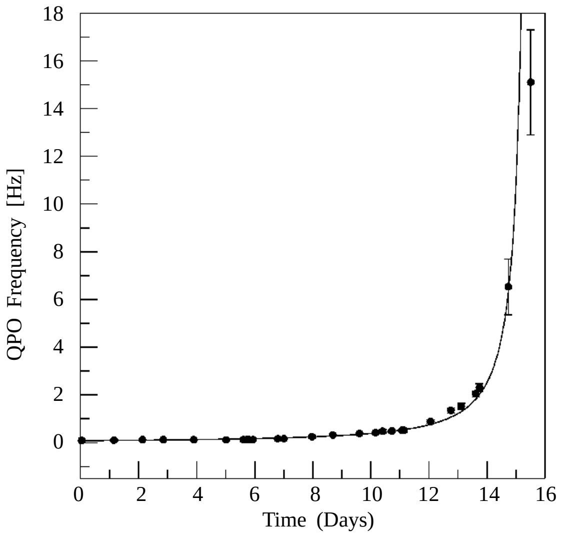

Figure 4. Observed centroid QPO frequencies (filled circles) of the first sixteen days are compared to the model solution (solid curve) which assumes oscillatory shock propagating towards the black hole with a constant speed. Error–bars indicating half line–widths obtained after fitting each power–density profile with a power–law for the background and a Lorentzian profile for the QPO. The final observation was made when the shock was at 97 Schwarzschild radii from the black hole.

In the earlier outburst, Remillard *et al* [7] also reported high frequency QPOs (at 300 Hz and 450 Hz) observed in this object. Since, as we understand it, the QPO frequency rises as the flow comes closer to the black hole, we expect to find QPOs at very high frequencies as well. In Figure 5. we show the plot of the PDS for the Obs-Id : 90428-01-01-00 (25/2/05). We concentrated only at high (> 100 Hz) frequencies. We find prominent power at ~689 Hz. This is totally absent in the low energy. To our knowledge, signatures of such high frequency QPOs have never been reported for any black hole candidates.

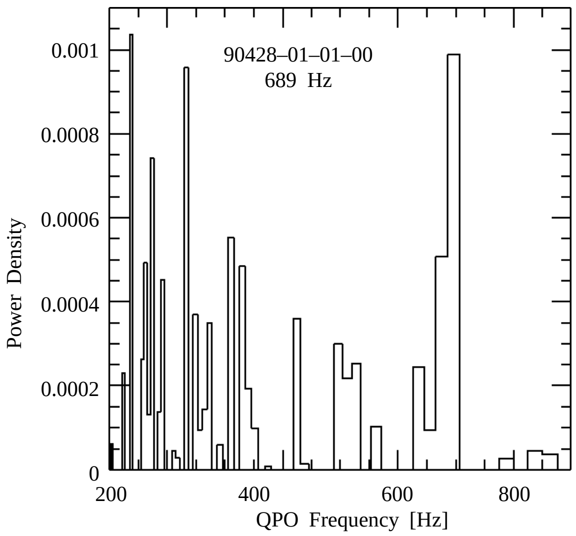

Figure 5. Possible signature of a high energy QPO in the current outbursting episode of GRO J1655–40. In the power density spectrum presented, a QPO at $\nu_{QPO} \sim 689$ Hz could be seen. This is the highest reported QPO for any black hole candidate in the literature.

4. Concluding remarks

In this communication, we analyzed in detail, two observations of RXTE data obtained during the most recent outburst of March, 2005. Our conclusion is that at the initial stage of the outburst, the shock was perhaps weaker and the energy dependence of the power density was not very strong. However, as the shock propagates, it also steepens and the energy dependence becomes stronger – harder energy photons show stronger and narrow band QPOs. We also computed the daily variation of the QPO frequency and fitted the daily variation of the observed frequency and found that the result agrees very well with the propagating shock wave model which is slowly moving towards the black hole. We find that on the last day on which the QPO was seen at $\nu_s \sim 15.01$ Hz, the shock was merely 38.7 Schwarzschild radius away from the black hole, though it started from a distance of 1200 on the 25th of February, 2005. By 15.6 days, the QPO and the shock disappeared completely which we interpret to be the disappearance of the shock behind the event horizon. However, weak shocks and perturbations continue to be advected. We caught a few such passages of shocks close to the black hole. We find indications that there may be QPOs in hard X-rays in 600 – 700 Hz range. For instance, we find ~689 Hz on 25/2/05. If we assume that our propagating shock model is correct, then, $\nu_{\rm QPO} \sim 689$ Hz corresponds to an emission from $r = 3.36$. For a Schwarzschild black hole, since shocks are expected to form farther than the 'O' type sonic point and thus, farther from $x = 6$ [8], we believe that the black hole could be a Kerr black hole. On the other hand, we are dealing with a 'propagating shock', hence some of the conclusions regarding a 'steady' shock need not be valid. In any case, for a non-rotating black hole, the highest QPO frequency we can have is of $\nu_{\rm max} = 835$ Hz (at $x = 3$). Unless we observe $\nu > \nu_{\rm max}$, the case for a Kerr black hole need not be compelling.

Acknowledgments

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