On the source of QPO of the black hole candidate GRS1915+105: some new observations and their interpretation.

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Abstract

A few classes of the light curve of the black hole candidate GRS 1915+105 have been analyzed in detail. We discover that unlike the previous findings, QPOs occasionally occur even in the so-called ‘On’ or softer states. Such findings may require a revision of the accretion/wind scenario of the black hole candidates. We conjecture that considerable winds which is produced in ‘Off’ states, cool down due to Comptonization, and falls back to the disk and creating an excess accretion rate to produce the so-called ‘On’ state. After the drainage of the excess matter, the disk goes back to the ‘Off’ state. Our findings strengthen the shock oscillation model for QPOs.

Key words: Black Hole Physics – Accretion Disks – Outflows – Stars:individual (GRS1915+105)

1 INTRODUCTION

The black hole candidate GRS1915+105 continues to excite astrophysicists by having one of the most, if not the most mysterious light curves. In a matter of days, the light curve changes its character, and within each day, photon counts show variations of a factor of two to five or more (Morgan, Remillard & Greiner, 1997; Belloni et al, 1997; Paul et al. 1998; Manickam & Chakrabarti 1999). The power density spectra shows clear evidence of quasi-periodic oscillations (QPOs) with frequency ranging from ~ 0.001Hz to 67Hz (see, e.g., Morgan, Remillard & Greiner, 1997; Chakrabarti & Manickam 2000, hereafter CM00, and references therein).

The origin of the quasi-periodic oscillations cannot be a complete mystery since there are very clear evidence that sub-Keplerian flows, which must occur in a black hole accretion, exhibit very wild time-dependent behaviour including large amplitude shock oscillations. This is true, especially when the infall time matches with the cooling time (Molteni, Sponholz & Chakrabarti, 1996; Ryu, Chakrabarti & Molteni 1997; Paul et al, 1998; Remillard et al, 1999a;b; Muno, Morgan & Remillard, 1999). This became more evident when it was observed that the QPOs are absent in low energy photons but is very strong at high energies, supporting the view that the photons participating in QPOs originate at hot post-shock flow (CM00, Rao et al. 2000). It has also been observed that QPOs are seen mostly when the photon counts are low (‘Off’ states) and QPO is very weak or absent in the On states when the photon counts are about two to five times larger. In the present Letter, by On and Off states, we would mean the high and low count states of the light curves. This nomenclature is not related to spectral states.

Because of the presence of the On and the Off states in the light curves, explanation of QPOs using radial oscillation of the centrifugal pressure supported shocks alone (which produce the right amplitude and frequency for the QPOs) cannot be the complete story. The very fact that the Off states terminate and the On states emerge in almost regular basis (but not exactly regular) gives rise to another time scale which must, at the same time, be dependent on disk/jet parameters. This is because Belloni et al. (2000) found that at least twelve types of light curves are seen, and within each type, the duration and behaviour of the On and the Off (if both exist) states were not at all fixed. For instance, $p$ class exhibits extremely regular light curves (Taam, Chen & Swank, 1997; Vilhu & Nevalainen, 1998) with broad Off- or low-count states and very narrow, spiky, high-count or On-states (see, Fig. 2b below). Light curves in the $\nu$ class...
is similar to those of $\rho$, but are highly irregular (see, Fig. 2a below). In $\lambda$ class, both Off and On states are of longer time duration (Belloni et al. 1997) while in $\kappa$ class these durations are relatively shorter (see, Fig. 5 below). Nandi, Manickam and Chakrabarti (2000) using a completely different procedure divided the light curves into four fundamental types (Hard, Soft, Semi-soft and Intermediate). The Intermediate class shows On/Off transitions. Chakrabarti (1999) and Chakrabarti & Manickam (2000) showed that outflow rates from the centrifugal barrier must play a major role in deciding the duration, as the wind matter at least up to the sonic sphere can be Comptonized and cooled down. Most of this cold matter (below the sonic surface of the cooler wind) can fall back on the immediate vicinity of the disk increasing its accretion rate temporarily while the rest must separate out at a supersonic speed. As this excess matter drains out, the Off state together with the QPO start appearing again.

In this Letter, we analyze light curves in detail and find that QPOs may be observed at very unlikely times in the light curves. For instance, we find that very often, there is a sharp peak (‘first hiccup’) at the onset of the On state and there is a sharp peak (‘last hiccup’) just prior to going to the Off state. The first peak, though in the On state, very often shows QPOs while the last peak, though the radiation is much harder, does not show a QPO. We also note that the radiation progressively hardens in the On state. In several cases, using data from both the RXTE and Indian X-ray Astronomical Experiment (IXAE), $\rho$ class curves (mostly mini-$\rho$ type) are seen to be peeled off from a $\kappa$ class. In $\kappa$ and $\lambda$, the On state duration is long and just before going to the Off state, the light curve becomes noisy and oscillating in nature, and the features indicate as though the light curve is made up of ‘sums’ of $\rho$ types. Only the lower half of the oscillations (local Off states of mini-$\rho$ states) exhibit QPO! We believe that these observations definitely point to the drainage of extra matter in the disk which was accumulated from the wind.

One of the problems in analyzing data of one of the most complex objects, such as GRS1915+105 is that one has to ask the right questions and as many of them as possible. Once a paradigm is kept in the back of the mind, asking questions become easier. We therefore concentrate on deciding the duration, as the wind matter at least up to the sonic speed. As this excess matter drains out, the Off state together with the QPO start appearing again.

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### 2 OBSERVATIONS

#### 2.1 Properties of two peaks in the On state

GRS 1915+105 exhibits both broad and narrow On states (Paul et al. 1998; Yadav et al., 1999; Belloni et al. 2000; CM00). When the On state is narrow or spiky, i.e., the duration with high photon counts is very small, and very often, just after transition from On to Off state, a second peak is observed. This has also been cursorily reported by Paul et al. (1998). Figure 1 shows details of a narrow section of the all-channel light curve corresponding to the RXTE observation of 15th of Oct. 1996 (The observation ID number is 10408-01-41-00.). We denote the peak appearing first as the primary peak (P1 for short) and the peak following P1 as the secondary peak (P2 for short) respectively. The words Off, ‘P1’ and ‘P2’ are marked. The entire light curve is almost a repetition of this section. Figure 2a presents the light curves of this data clearly showing two peaks P1 and P2 in the On state. The time lag between the two peaks is roughly constant on a given day (in this case about 10 seconds) and we do not find any correlation between this lag and the duration of the Off state. The light curve is shown in four panels: the panels are drawn for channel energies (from top to bottom) 0 – 5.07keV, 5.43 – 6.88keV, 7.24 – 9.43keV, and 9.79 – 13.09keV respectively (corresponding channels are 0 – 13, 14 – 18, 19 – 25, 26 – 35 respectively). Note that while in low energies, photon counts in P1 is much larger compared to P2, in higher energies they are roughly equal, suggesting that the spectrum of P2 is harder. Taam, Chen and Swank (1997) also noted the existence of these peaks and that P2 is harder compared to P1. A similar light curve is shown in Fig. 2b, for the RXTE observation of 22nd of June, 1997 (see also Vilhu & Nevalainen (1998) and Yadav et al (1999) for displaying this light curve.). The corresponding observation ID is 20402-01-34-01. In this case, the time lag is about 4 seconds but other features are similar to those of Fig. 2a. The channel energies are marked on each panel (corresponding channels numbers are 0 – 13, 14 – 19, 20 – 25, 26 – 35 respectively).

Figures 3(a-c) show the power density spectra (PDS) of the three regions marked in Fig. 1. While selecting photons from ‘P1’ and ‘P2’ regions we took special care that they are not contaminated by the photons from the Off states. Also, to improve statistics, we added data from many peaks over the entire duration of the observation on that day. Note that in the Off state there is a distinct QPO of frequency $\nu_{\text{qpo}} = 7.4Hz$. Photons in ‘P1’ also exhibit QPO though it is weaker ($\nu_{\text{qpo}} \sim 5.7Hz$). QPO is completely absent from ‘P2’.
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Fig. 2a: Four panels showing light curves of a part of the observation on Oct. 15th, 1996 (ID: 10408-01-41-00) at different channels (energies are marked). Note that ratio of photon counts in P1 and P2 tends to become unity at higher energies.

Fig. 2b: Four panels showing light curves of a part of the observation on June 22nd, 1997 (ID: 20402-01-34-01) at different channels (energies are marked).

We examined the RXTE data of 22nd June, 1997 also, the PDS of which is shown in Fig. 4(a-c). The result is generally the same. The QPO frequency in the Off-state is given by \( \nu_{\text{qpo}} = 6.3 \text{Hz} \) and in P1 peak \( \nu_{\text{qpo}} = 6.8 \text{Hz} \). We therefore believe that the observed features may be generic.

Fig. 3(a-c): Power Density Spectrum (PDS) of three regions marked in Fig. 1 of the observation dated Oct. 15th, 1996. Several data segments have been added to improve statistics. Note the absence of QPO in P2.

Fig. 4(a-c): Power Density Spectrum (PDS) of three regions marked in Fig. 1 of the observation dated June 22nd, 1997. Several data segments have been added to improve statistics. Note the absence of QPO in P2.

2.2 Properties of On++ state

It is generally observed that whenever the duration of On or the high count state is large, light curves become very noisy and count rates start oscillating wildly as the Off state is approached. The later half may be termed as ‘On++’ state and Manickam & Chakrabarti (1999) showed that this region exhibits a weak QPO. In fact, similar to Fig. 2(a-b) above, where the photons in P2 are harder compared to P1, one finds that On++ state is harder compared to the first half of the On state. This is demonstrated in Fig. 5,
First note that RXTE and IXAE show very similar behaviours throughout the period of overlap of observations. Second, towards the end of each of the On states (which we term as On$^{++}$ state for brevity), the light curves are noisy and generally oscillatory in nature. Third, in both the experiments, the relative oscillations are increased with the increasing photon energy in On$^{++}$ state. Fourth, though generally the light curve may be called that of a $\kappa$-class (Belloni et al. 2000), several pieces of $\rho$ class is evident. In fact, mini-$\rho$ type light curves are also evident in the On$^{++}$ states giving clear evidence that the light curve in the $\rho$-class is more primitive. In the next Section we discuss possible interpretations of this important observation.

In Fig. 6, we show a part of the light curve on the same day, and draw two boxes (in dotted curves) at the On$^{++}$ state. The photons from the upper box show no sign of QPO, while the photons from the lower box shows clear evidence of QPO. Since lower box contains photons which are from mini-Off states of the mini-$\rho$ class mentioned above, it is not surprising that this show QPOs. Indeed, while the Off state on this day shows QPO of frequency 3.09Hz, these mini-Off states show QPOs of frequency 6.25Hz. This indicates that towards the end, the shock again starts developing much closer to the black hole giving rise to a higher oscillation frequency and when the shock is fully developed, the Off state begins with a QPO at 3.09Hz.

An easily missed phenomenon in all these light curves is that most of the On states begin with a ‘hiccup’ or a small peak, which may be likened with ‘P1’ of $\rho$ or $\nu$ class and also end with another ‘hiccup’ which may be likened with ‘P2’.

3 POSSIBLE INTERPRETATIONS OF THESE OBSERVATIONS

3.1 The Paradigm

While there is as yet no fully self-consistent model which includes disks, winds and radiative transfer simultaneously, one can collect bits and pieces of the solutions and construct a viable model for the system. Chakrabarti (1996) and more recently Chakrabarti (2000a) have discussed such solutions in detail. Fig. 7 shows a cartoon diagram of an accretion/wind system of GRS 1915+105. Generally, it is assumed the the accretion is advective in nature and has a centrifugal barrier dominated region which may or may not have become a fully developed shock (at $r = r_s$) throughout the period of observation. Chakrabarti (1999) showed that the centrifugal barrier dominated boundary layer (CENBOL for short) is not only responsible for the Comptonized radiation, but also responsible for the wind/jet formation. A very simple analysis which envisages an isothermal wind at least up to the sonic surface (at $r = r_s$) shows that winds should not be emitted in soft states, and very hard states should have very little winds. If the shock is of intermediate strength, outflow rate is very much high.

If the outflow rate is high enough, it can fill the sonic sphere (of size $r_s \sim 2 - 3 r_s$; sub-sonic region up to the sonic surface) rapidly till the optical depth due to Compton scattering become larger than unity. Comptonization cools down this region rapidly. CM00 suggests that the duration of the Off state is the time in which this region achieves this threshold of cooling. Since the specific energy and angular momentum of the flow decide shock location and its strength (Chakrabarti 1989), a small variation of the overall viscosity would change the shock location, and therefore cause the variation of the duration and the QPO frequency from one Off state to another. The correlation between duration and frequency based on this consideration has been discussed in CM00. An important bye-product of all these is that as the disk loses matter (and pressure) from the post-shock region in the form of outflows, the shock, as well as the inner edge of the Keplerian disk moves inwards, gradually increasing the QPO frequency. This has been demonstrated by the dynamic power density spectra (e.g., Muno et al., 2000; Trudolyubov et al. 2000).

A part of the wind which does not reach escape velocity must return back to the disk and the accretion rate of the disk is temporarily modulated. This has been demonstrated by two dimensional simulations of advective disks (Molteni, Lanzafame & Chakrabarti, 1994; Molteni, Ryu and Chakrabarti, 1996 and Ryu, Chakrabarti & Molteni, 1997). This feedback mechanism becomes more complex in presence of radiative cooling of the outflow. After the wind is cooled down, the sound speed is reduced, and location of the sonic surface comes closer to the black hole, very abruptly.
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Part of the originally subsonic outflowing matter still remains below the new sonic surface and falls back since it loses drive to escape. The rest becomes supersonic (because of reduced sound speed) and separates in the form of blobs. Thus, blobs are produced at the end of the off-states. This conjecture has been tested by multilengthwave observations (Dhawan et al. 2000).

During the On states, the shock and the CENBOL are non-existent and hence the QPOs are generally absent. Towards the end of the On state, in the so-called On$^{++}$ state, the shocks start forming close to the black hole because of heat generated by excess accretion. The shock then rapidly recedes to a distance consistent with the steady state solution as soon as the excess matter is drained out of the disk. This causes the onset of the Off state. This process of receding are regularly seen in numerical simulation of sub-Keplerian flows (Chakrabarti & Molteni, 1993; MLC94).

3.2 Origin of hiccups or P1 and P2 peaks

It is clear that since these peaks are separated by a few seconds, and generally one has a QPO while the other does not, their origins cannot be the same. From the paradigm described above, one may imagine that P1 forms when catastrophic cooling of the CENBOL-sonic sphere system takes place. Since P1 is a continuation of the Off state, QPO is thus expected unless the shock is hidden under the cooler wind. P2 is due to the steepening of last bits of excess matter on the disk which is delayed by the viscous time-scale. The viscous time which a ring of matter takes after it leaves the Keplerian disk from a transition radius ($r_{tr}$, where the flow deviates from a Keplerian disk (Chakrabarti & Titarchuk, 1995), and enters the post-shock region is given by $t_{visc} \sim \left(\frac{c_s}{c_s}\right)^{2/r_{Kep}} = 10(0.01)^2(0.1)^{1/2}s$ where $\alpha$ is the Shakura-Sunyaev viscosity parameter, $h(r) \sim c_s r^{3/2}$ is the dimensionless instantaneous height of the disk (in vertical equilibrium) at a radius $r$ (measured in units of $R_g = 2GM/c^2$, the Schwarzschild radius), $v_{Kep}$ is the rotational velocity of the Keplerian orbit, and $c_s$ is the speed of sound in units of velocity of light. As this ring of matter propagates through this region, it is illuminated by soft photons coming out of the Keplerian disk, but since it is outside the shock, its radiations do not participate in the oscillation. On the other hand, since rising side of P1 is in Off state, it shows QPO. Due to Compton cooling the spectrum of P1 is softer. However P2 occurs when the excess matter is almost entirely drained out from the disk. Hence its spectrum is harder.

It is to be noted that whether or not shocks would form depend on viscosity. It has been shown (Chakrabarti, 1990; Chakrabarti & Molteni, 1995; Chakrabarti 1996) that there is a critical viscosity parameter $\alpha_c$ below which shocks can form and this parameter is about $\alpha_c \sim 0.015$. Beyond this chokes disappear and Keplerian flows directly enter into the black hole. Out choice of $\alpha = 0.01$ to explain the time scale is thus consistent with the presence of shocks.

In general, as excess matter drains out of the CENBOL,
its optical depth decreases and the spectrum gets harder in
the On$^{++}$ state. This is observed in both RXTE and IXAE
data.

3.3 Origin of $\rho$ type light curve

One of the reasons we plotted Fig. 5 using the particular re-

region of $\kappa$ class observations is that it may hold the key of un-

derstanding the general light curves. The Figure clearly in-

dicates that $\rho$ type regions are peeled off gradually in On$^{++}$

states of $\kappa$ class light curve. Arrows in Fig. 5 indicate that

the forms of rise and fall are qualitatively similar, but quan-

titatively one is a miniature version of a fully developed $\rho$

type of bursts. Details of the modeling is being discussed

elsewhere (Chakrabarti et al. 2000b).

Briefly, when the entire CENBOL behaves like a single blob, it's

light curve is of $\rho$ type: count rate going up in Comptonization

time scale and rapidly drops in infall time-

scale. However, in presence of strong winds, and subsequent

return of matter on the disk, turbulence are generated and

one may imagine that each of the turbulent cells after being

steepened into small shocks, producing mini-$\rho$ light curves,

depending on the shapes and sizes of the turbulent cells.

Each mini-shock produces a mini-$\rho$ curve after filing smaller

sonic surface.

4 CONCLUDING REMARKS

In this Paper, we have pointed out some new and interesting

behaviour of the light-curve of the black hole candidate GRS

1915+105. We showed that very often the On states of $\rho$ and $\nu$
types of light curves produce more than one peak which

behave differently. For instance, the first peak may show

QPOs whereas the second peak shows no QPO. The second

peak also has a harder spectrum. In the $\kappa$ and $\lambda$ classes

when the On state duration is longer, the On state shows

very noisy and oscillatory behaviour towards the end, which

we term as On$^{++}$ state. What is more, photons from upper-

half of these light curves do not show QPOs while those from

the lower-half do.

Though these observations are related to very small re-

gions of the overall light curves, they help us understand the

behaviour of matter close to a black hole. If one assumes that

the duration of the Off states are determined by the time in

which the optical depth of the sonic sphere becomes unity,

as CM00 suggested, then many puzzles are resolved. In this

picture, part of the cooler matter of the outflowing wind

falls back on the CENBOL and the pre-shock disk and its

drainage time gives rise to the On states. It is possible that

the first catastrophic cooling gives rise to the first hiccup

in the On state and the last significant density perturba-
tion due to the fallen matter may cause the final hiccup.

This can explain why P1 often shows QPO, but P2 does

not. Duration of On states in between may vary, depend-
ing on drainage time, giving rise to various classes of light
curves. Also, towards the end of the drainage period, i.e., in

On$^{++}$ states, the excess matter is depleted and the signs of

QPO starts appearing. What is most interesting, mini-Off

states show QPO, while mini-On states do not, indicating

that states with broader On are possibly made of $\rho$ type

bursts.

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REFERENCES

Belloni, T, Méndez, King, A.R., Van der Klis, M. & Van Paradijs,
J. 1997, APJ 488, L109
Belloni, T., Klein, Wolt, M., Méndez, M., van Der Klis, M. and
van Paradijs, J. 2000, A & A, 355, 271
Chakrabarti, S.K. 1989, ApJ 347, 365
Chakrabarti, S.K. 1990, M.N.R.A.S. 243, 610
Chakrabarti, S.K. & Molteni, D., 1995, M.N.R.A.S. 272, 80
Chakrabarti, S.K. 1996, Phys. Rep., 266, 229
Chakrabarti, S.K. 1999a, Ind. J. Phys. 73B(6), 931
Chakrabarti, S.K. 1999b, A&A 351, 185, (C99)
Chakrabarti, S.K. 2000a, Il Nouvo Cimento (In press).
Chakrabarti, S.K. et al. 2000b, Proceedings of 9th Marcel Gross-
man meeting (Ed.) R. Ruffini
Chakrabarti, S.K. & Molteni, D. 1993, ApJ 417 671
Chakrabarti, S.K. & Manickam, S.G. 2000, ApJL 531, L41
(CM00)
Chakrabarti, S.K. & Titarchuk, L.G. 1995, ApJ 455, 623
Dhawan, V., Mirabel, I. F. & Rodriguez, L. F. 2000, ApJ, sub-
mitted.
Manickam, S.G. & Chakrabarti, S.K. 1999 in Proceedings of
Young Astrophysicists of Today’s India, Ind. J. Phys. 73(6),
967
Molteni, D., Lanzafame, G. & Chakrabarti, S.K. 1994, ApJ 425,
161
Molteni, D., Sponholz, H. & Chakrabarti, S.K. 1996, ApJ 457,
805
Molteni, D., Ryu, D. & Chakrabarti, S.K. 1996, ApJ 470, 460
Morgan, E. H., Remillard, R. A. & Greiner, J. 1997, ApJ 482, 993
Muno, M.P., Morgan E.H. & Remillard, R.A. 1999 ApJ 527, 321
Muno M.P., Morgan E.H., Remillard, R. A. 1999, 527, 321.
Nandi, A., Manickam, S. & Chakrabarti, S.K., 2000, Ind. J. Phys.,
74B(5), 3312
Paul, B., et al. 1998, ApJ 492, L63
Rao, A.R, Naik, S.,Vadawale, S.V. And Chakrabarti, S.K. 2000,
A&A, 360, L25
Remillard, R.A. et al. 1999a ApJL 517, L127
Remillard, R. A., Morgan, E.H., McClintock, J.E., Bailyn, C. D.,
Orosz, J.A. 1999b, ApJ 522, 397
Ryu, D., Chakrabarti & Molteni, D. 1997, ApJ 474, 378
Taam, R., Chen, X.-M. & Swank, J. 1997, ApJ, 485, 83
Trudolyubov S., Churazov E., Gilfanov, M. 1999, A & A 25, 718
Vilhu, O. & Nevalainen, J. 1998, ApJ, 508, L85
Yadav, et al., 1999, ApJ, 517, 935

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