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The $1-12$ Hz QPOs and dips in GRS 1915+105: tracers of Keplerian and viscous time scales?

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Abstract. We analyzed 9 *RXTE*/PCA observations of GRS 1915+105 in the flaring state, when the hardness of the source spectrum was changing on the time scales from few seconds up to 1000 seconds. The quasi periodic oscillations (QPOs) with the frequency varying between ~ 1 and 12 Hz are associated with the episodes of harder source spectrum. In each observation we found tight correlation between the duration of the hard episode and the characteristic QPO frequency. For a half of the observations this correlation matches the relation between the viscous time scale and the Keplerian frequency, when both quantities are evaluated for various radii in the radiation pressure dominated accretion disk. Assuming that the QPO frequency is proportional to the Keplerian frequency at the boundary between an optically thick accretion disk and a hot comptonization region, the changes of the QPO frequency can then be understood as due to variations of this boundary position on the viscous time scales.

Key words: stars: binaries: general – stars: individual: GRS 1915+105 – X-rays: stars

1. Introduction

The X-ray source GRS 1915+105, one of the several galactic objects producing observable superluminal jets (Mirabel & Rodriguez 1994), was discovered by *GRANAT* observatory as a transient in 1992 (Castro-Tirado, Brandt & Lund 1992). Long-term monitoring of GRS 1915+105 with *RXTE* revealed repetitive character of the source variability patterns. Basing on the results of spectral and timing analysis, bursting behavior of the source can be roughly reduced to the sequence of varying 'hard' and 'soft' states qualitatively distinguished by their spectral and temporal properties (Belloni *et al.* 1997*a*, *b*; Markwardt *et al.* 1999; Muno *et al.* 1999).

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Table 1. The list of *RXTE*/PCA observations of GRS 1915+105 used for the analysis.

Obs.ID	Date, UT	Start, UT	Exp.[a], s
10408-01-01-01	06/04/96	05:39	5068
10408-01-10-00	26/05/96	17:12	6128
10408-01-38-00	07/10/96	05:44	9766
10408-01-44-00	25/10/96	11:52	8250
20402-01-01-00	07/11/96	05:42	6948
20402-01-28-00	18/05/97	16:19	7349
20402-01-33-00	18/06/97	12:58	6093
20402-01-35-00	07/07/97	14:53	5718
20402-01-59-00	17/12/97	02:10	8795

[a] – Deadtime corrected value of the PCA exposure

2. Observations and data analysis

The observations used for the analysis are listed in Table 1. For the timing analysis in the $2-30$ keV energy range the *RXTE*/PCA (Bradt, Swank & Rothschild 1993) data in the 'binned' and 'event' modes containing X-ray events below and above 13 keV respectively were used. We generated power density spectra (PDS) in the $0.25-150$ Hz frequency range accumulated in the 4 s time intervals (Leahy *et al.* 1983). The PDS were linearly rebinned into 0.25 Hz bins. The white-noise level due to Poissonian statistics corrected for the dead-time effects was subtracted. For the determination of the QPO centroid frequencies the PDS were fitted to the analytic model consisting of a Lorentzian profile and a power law continuum in the $0.5-15$ Hz frequency range (typical error of the derived value of the QPO frequency is $\sim 0.2-0.3$ Hz).

3. Results

Two typical examples of GRS 1915+105 X-ray flux histories in the $2-30$ keV band are presented in Fig. 1 along with hardness ratios ($13-30$ keV to $2-13$ keV) and dynamic PDS integrated over 4 s time intervals. The source behavior in the flaring state is characterized by frequently occurring episodes of hard energy spectrum last-

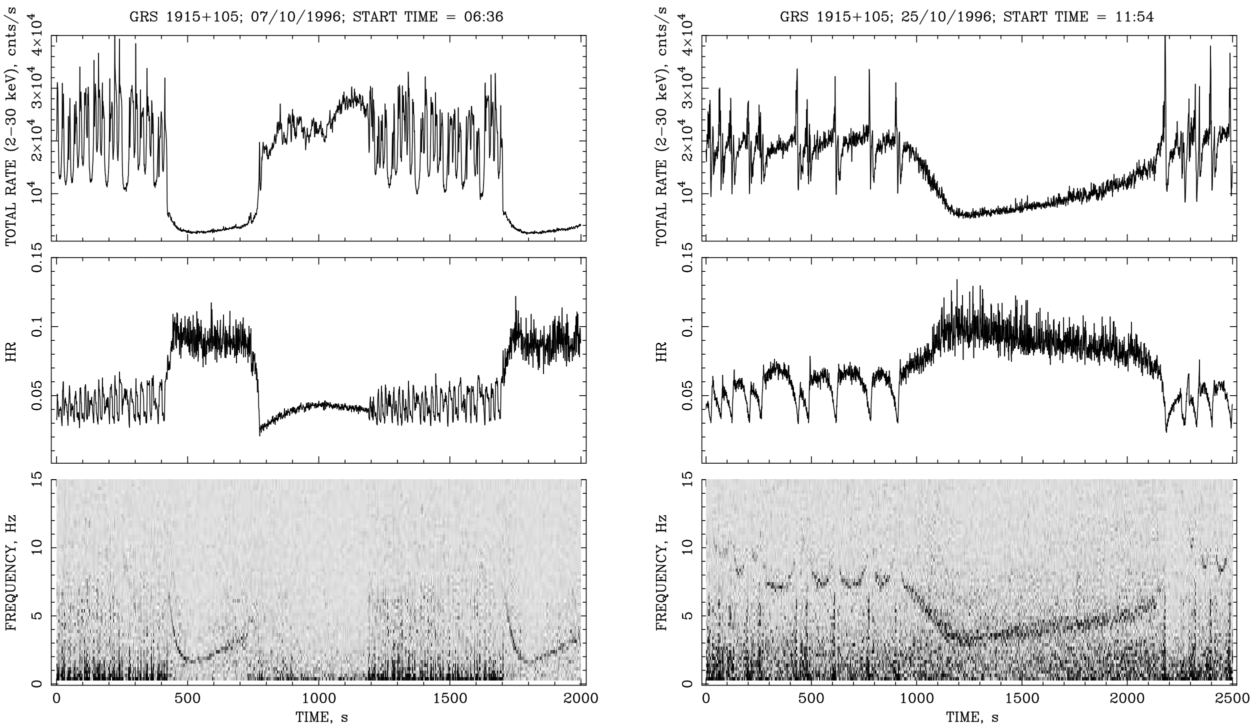

Fig. 1. Part of the light curves (*upper panels*), corresponding hardness ratios $(13-30\ \mathrm{keV})/(2-13\ \mathrm{keV})$ (*middle panels*) and dynamic PDS (*lower panels*) of GRS 1915+105 for the Oct. 7, 1996 (*left panels*) and Oct. 25, 1996 (*right panels*) observations ($2-30$ keV energy band, PCA data). The QPO peak appears as 'U'-shaped dark band in the *lower panels*. The light curves were not corrected for the instrument dead time which was $5-20\%$. The overall count rate corresponds to 5 Proportional Counter Units of the PCA detector.

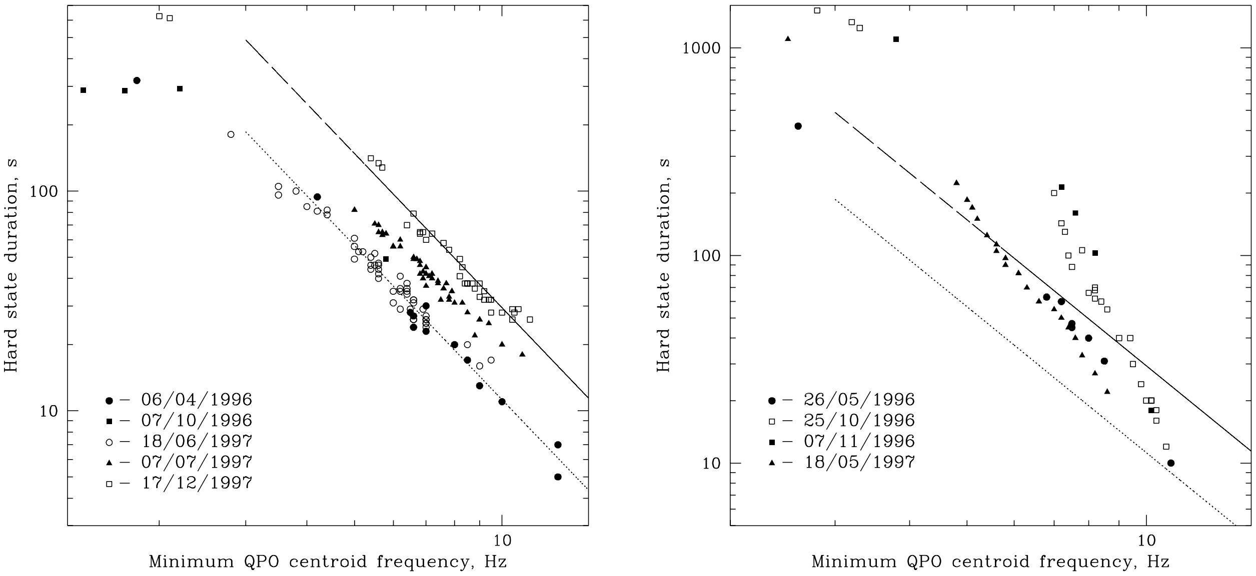

Fig. 2. The relation between the duration of a hard episode and a corresponding minimal QPO frequency for the flaring state observations listed in Table 1 (first group – *left panel*; second group – *right panel*). The dependences $t_{\rm visc} \propto f_{\rm K}^{-7/3}$ of the viscous time scale upon the Keplerian frequency at the inner edge of the radiation pressure dominated disk with the mass accretion rate $\dot{m} \sim 0.11(\alpha/0.1)^{-1/2}(m/33)^{-2/3}$ and $\dot{m} \sim 0.17(\alpha/0.1)^{-1/2}(m/33)^{-2/3}$ are shown in the *left and right panels* by long-dashed and dotted lines respectively (see text).

ing typically $10-1000$ s. The prominent, relatively narrow variable-frequency $1-12$ Hz QPO peak (dark 'U'-shaped band in the *lower panels* in Fig. 1) is a generic feature of the source power density spectrum during hard episodes (Markwardt *et al.* 1999; Muno *et al.* 1999).

Using the data from our sample of flaring state observations (Table 1), we studied the relation between the duration of a hard episode, t_{hard} (determined using the hardness ratio) and the lowest value of the QPO frequency reached (determined from the fitting of the PDS to the analytical model). In Fig. 2 the duration of a hard episode is plotted as a function of the minimal QPO frequency. For all observations used in the analysis there is a strong anticorrelation between these two quantities. The dependence has a nearly power law form for durations of a hard episode shorter than $\sim 100-200$ s and probably flattens for longer events. According to the value of the slope Γ of this power law dependence the observations can be subdivided into two groups: $\Gamma \sim 2.1-2.4$ for the 06/04/96, 07/10/96, 18/06/97, 07/07/97 and 17/12/97 observations (the first group, *left panel* in Fig. 2) and $\Gamma \geq 3.0$ for the 26/05/96, 25/10/96, 07/11/96 and 18/05/97 observations (the second group, *right panel* in Fig. 2). The analysis of the flux histories showed that these two groups have qualitatively different lightcurves: for the first group the transition from 'hard' to 'soft' state is characterized by the growth of the $2-30$ keV flux (Figure 1, *upper left panel*), while for the second group this transition corresponds to the decrease of the X-ray flux (Figure 1,*upper right panel*). In the subsequent paper (Trudolyubov *et al.* 1999*b*) it will be shown that these two groups are also distinguished by the properties of their energy spectra: for the first group the soft thermal component makes a significant contribution to the overall luminosity in the $3-20$ keV energy range, for the second group the energy spectrum is dominated by the hard component (the contribution of the soft thermal component to the total luminosity is $< 25\%$).

4. Discussion

The study of the spectral and temporal evolution of GRS 1915+105 during the periods of flaring activity has shown that bursting behavior of the source can be reduced to a sequence of varying hard and soft episodes. The hard episodes are distinguished by the presence of the prominent QPO peak in the source power density spectrum. Combined time-resolved spectral and timing analyses revealed (i) a strong correlation between the QPO frequency and parameters of the soft component of the energy spectrum (presumably emitted by the optically thick part of the disk) on a wide range of time scales (Trudolyubov *et al.* 1999*a*; Markwardt *et al.* 1999; Muno *et al.* 1999); (ii) the dependence of the duration of the hard episode upon the corresponding characteristic radius of the optically thick disk (derived through the spectral fitting with multicolor disk black body model) $t_{\rm hard} \propto r^{7/2}$ is similar to that expected if the duration of the hard episode is proportional to the viscous time scale of the radiation pressure dominated disk (Belloni *et al.* 1997*b*). Given (i) and (ii) some sort of correlation between the QPO frequency and the duration of the hard episode is naturally expected.

To explain the observational properties of black hole and neutron star binaries in the *hard* state a number of models involving the hot comptonization region near the compact object surrounded by the optically thick accretion disk was proposed. It is often assumed that the QPO phenomenon is caused by interaction between these two distinct parts of the accretion flow occurring on the local dynamical time scale at the boundary of these regions (Molteni *et al.* 1996; Titarchuk, Lapidus & Muslimov 1998). In the following analysis we will also assume that the QPO frequency is proportional to the Keplerian frequency at the inner boundary of the accretion disk.

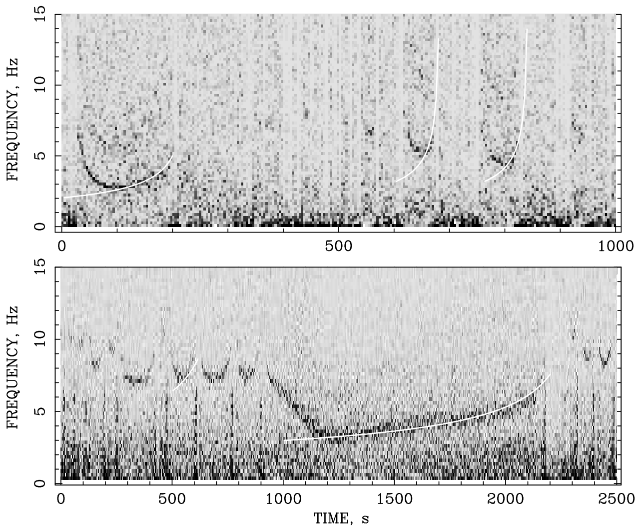

Fig. 3. Dynamic power density spectra for two representative observations (18/06/1997 – first group (*upper panel*, 25/10/1996 – second group *lower panel*). The expected time dependence of the QPO frequency implied by viscous evolution of the radiation pressure dominated part of the accretion disk is presented by a white solid lines superimposed on the observed QPO track.

In the standard accretion disk theory (Shakura & Sunyaev 1973) the viscous time of the radiation pressure dominated disk is $t_{\rm visc} \sim 1.2 \times 10^{-5} \alpha^{-1} m \dot{m}^{-2} r^{7/2}$ s, where α – viscosity parameter, m – mass of the compact object in solar masses, $\dot{m}$ – disk accretion rate in units of critical Eddington rate, r – distance to the compact object in units of 3 gravitational radii. Introducing the local Keplerian frequency, $f_{\rm K} \approx 2200\, m^{-1} r^{-3/2}$ Hz, we obtain:

$$t_{\rm visc} \sim 740 \alpha^{-1} m^{-4/3} \dot{m}^{-2} f_{\rm K}^{-7/3} \;\; s \qquad (1)$$

This dependence, $t_{\rm visc} \propto f_{\rm K}^{-7/3}$, reproduces well the relation between the duration of a hard episode and the associated minimal QPO frequency for the first group of observations (Fig. 2, *left panel*). Moreover, for several observations from this group the observed relation between the duration of a hard episode and the maximal value of the characteristic inner radius of the disk, determined via spectral fitting, matches remarkably well the expected dependence of the viscous time scale on the radius for the radiation pressure dominated disk (Belloni *et al.* 1997*b*).

Assuming that the QPO frequency is proportional to the Keplerian frequency ($f_{\rm QPO} = f_{\rm K}/l$) and duration of the hard episode is proportional to the viscous time ($t_{\rm hard} = t_{\rm visc}/k$), one can estimate the required mass accretion rate $\dot{m}$ using equation (1):

$$\dot{m} \sim \left(\frac{\alpha}{0.1}\right)^{-1/2} \left(\frac{m}{33}\right)^{-2/3} \left(\frac{k\, t_{\rm hard}}{100s}\right)^{-1/2} (l f_{\rm QPO})^{-7/6} \quad (2)$$

In Eq. (2) compact object mass was normalized to the value of 33 $M_{\odot}$, implied by the interpretation of the 67 Hz QPO feature as a signature of a Keplerian oscillations near the last marginally stable orbit around a Schwarzschild black hole (Morgan *et al.* 1997). The inferred values of the accretion rate for the observations from the first group are in the range $\dot{m} \sim (0.11 - 0.17)(\alpha/0.1)^{-1/2}(m/33)^{-2/3} k^{-1/2} l^{-7/6}$ (Fig. 2). This conclusion is supported by the results of the spectral analysis (Trudolyubov *et al.* 1999*b*) where the bolometric luminosity of the soft spectral component corresponding to a given value of QPO frequency was used as a measure of the mass accretion rate.

If the QPO frequency is associated with the selected region in the accretion disk (e.g. inner edge of the optically thick disk) which is moving radially on the viscous time scale, then we expect correlation of the QPO frequency and the rate of the frequency change. Assuming that rise of the QPO frequency is caused by the inward motion of the inner edge of the radiation pressure dominated accretion disk one can write:

$$\left(\frac{df_{\rm QPO}}{dt}\right) = \left(\frac{df_{\rm QPO}}{dr}\right) v_{\rm r}(r) \sim \alpha \dot{m}^2 m^{7/3} f_{\rm QPO}^{10/3}, \qquad (3)$$

where $v_{\rm r}(r)$ – radial velocity of the matter in the disk at radius r (Shakura & Sunyaev 1973). Integrating Eq. (3), we obtain:

$$f_{\rm QPO}^{-7/3}(t_0) - f_{\rm QPO}^{-7/3}(t) = A(t - t_0), \qquad (4)$$

where $A \sim \alpha \dot{m}^2 m^{7/3}$. In Fig. 3 this dependence is shown in comparison with the observed QPO evolution for two observations from the first (18/06/1997) and the second (25/10/1996) groups. For the first group both initial decrease and following rise of the QPO frequency during the hard episodes are generally described by Eq. (4) (Fig. 3, *upper panel*) but with different values of coefficient A. For the rise phase the value of coefficient A remains practically the same on a time scale of an individual observation ($\sim 10^4$ s). For the second group of observations only rise of the QPO frequency is generally described by Eq. (4), while the initial decay often has a more complicated structure (Fig. 3, *lower panel*). In addition, an extended plateau in the time dependence of the QPO frequency near its minimum is sometimes present. This might explain the deviation of the dependence of $t_{\rm hard}$ on the QPO frequency from the $t_{\rm hard} \propto f_{\rm QPO}^{-7/3}$ law for the second group of observations.

5. Conclusions

We analyzed the temporal behavior of GRS 1915+105 using the set of 9 *RXTE*/PCA observations representing typical patterns of the source X-ray evolution during the periods of flaring activity.
1. For all individual observations the tight correlation between the duration of a hard episode and the minimal QPO frequency was found.
2. For ∼half of the observations this correlation is satisfactory described by the standard radiation pressure dominated disk theory assuming that the QPO frequency and the duration of a hard episode are proportional to the Keplerian frequency and the viscous time on the inner edge of the disk respectively. The derived values of the mass accretion rate for these observations are in the range $\dot{m} \sim (0.1 - 0.2)(\alpha/0.1)^{-1/2}(m/33)^{-2/3}$. Not all observations fit this dependence. In fact for the large fraction the relation $t_{\rm hard} \propto f_{\rm QPO}^{-7/3}$ breaks. It should be noted, that for these observations the correlation $t_{\rm hard} \propto r^{7/2}$ (Belloni *et al.* 1997*b*) also fails.
3. The temporal evolution of the QPO frequency during the rise phase of the hard episodes can be explained as a change of the Keplerian frequency at the inner edge of optically thick accretion disk caused by its viscous motion.

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