Neutron Stars and Pulsars: Challenges and Opportunities after 80 years
Proceedings IAU Symposium No. 291, 2012
J. van Leeuwen, ed.

doi:10.1017/S1743921312024891

On the origin of the low-frequency QPO in GRS 1915+105 ρ state

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Abstract. We performed a phase-resolved timing analysis of GRS 1915+105 in its ρ state and identify detailed ρ cycle evolution of frequency, amplitude and coherence of the low-frequency quasi-periodic oscillation (LFQPO). We combined our timing results with the spectral study by Neilsen *et al.* (2011) to do an elaborate contrast analysis. The results are naturally explained by tying the LFQPO to the corona.

Keywords. accretion, accretion disks, oscillations, GRS 1915+105

1. Introduction

GRS 1915+105 is a binary system which was discovered by the WATCH instrument on board *GRANAT* in 1992 (Castro-Tirado *et al.* 1992). It is located in our galaxy at an estimated distance of about 11 kpc (e.g., Fender *et al.* 1999; Zdziarski *et al.* 2005), containing a spinning black hole (Zhang *et al.* 1997; McClintock *et al.* 2006) with mass about 14 ± 4 $M_\odot$ and a K-M III giant star with mass 0.8 ± 0.5 $M_\odot$ as the donor (Harlaftis & Greiner 2004; Greiner *et al.* 2001). As the first found microquasar, GRS 1915+105 produces superluminal radio jets (Mirabel & Rodríguez 1994; Fender *et al.* 1999). The count rate and color characteristics are extremely complex, and the light curves of the source are usually classified into 12 variability classes (Belloni *et al.* 2000).

Research on GRS 1915+105 has revealed that the its LFQPO frequency is positively correlated with the flux of the thermal and power law components and total intensity (e.g., Chen *et al.* 1997; Markwardt *et al.* 1999; Muno *et al.* 1999, 2001; Trudolyubov *et al.* 1999; Tomsick & Kaaret 2001). The LFQPO amplitude is inversely correlated with the source flux or LFQPO frequency (e.g., Muno *et al.* 1999; Reig *et al.* 2000). As the LFQPO frequency increases, the temperature of the inner accretion disk increases and the radius of the inner accretion disk decreases (e.g., Rodriguez *et al.* 2002a). The LFQPO amplitude increases with photon energy and it turns over in high energy bands in some cases (e.g., Tomsick & Kaaret 2001; Rodriguez *et al.* 2002b, 2004; Zdziarski *et al.* 2005). As the centroid frequency of LFQPO increases, the corralation between LFQPO frequency and photon energy evolves from negative to positive (Qu *et al.* 2010). In addition, three more combined patterns of negative to positive correlation were discovered (Yan *et al.* 2012).

Although the results mentioned above enable a good understanding of LFQPO, we are puzzled by the ambiguous fact that LFQPO is correlated with both corona/jet and accretion disk. Neilsen *et al.* (2011; hereafter NRL11) investigated the physical changes and the LFQPO evolution of the ρ variability in GRS 1915+105 through a phase-resolved spectral and timing analysis. In order to reveal more clues about the origin of the LFQPO and more details about evolution of the ρ cycle, we follow up in this work with a detailed contrast analysis between the results of spectral and timing analyses.

2. Data reduction and results

Using a method similar to that of NRL11, we do a phase-resolved timing analysis for 60405-01-02-00, the same *RXTE* observation of GRS 1915+105 analyzed by NRL11.

For each 0.02 phase interval the power density spectrum (PDS) is computed in the 2.0 − 37.8 keV band and the results are shown in Fig. 2. The phase-folded PCA ρ class lightcurve (Fig. 2a) and the 0.5 − 10 Hz amplitude shape (Fig. 2b) are similar to those of NRL11. Based on the behavior of the LFQPO amplitude (Fig. 2d), the cycle phase is divided into six intervals (I: 0.02 − 0.12, II: 0.12 − 0.26, III: 0.26 − 0.4, IV: 0.4 − 0.74, V: 0.74 − 0.92, and VI: 0.92 − 0.02). In the interval I, there is no obvious LFQPO. In intervals II and VI, the LFQPO amplitude is positively correlated with the LFQPO frequency. While in intervals III, IV and V, the LFQPO amplitude is negatively correlated with the LFQPO frequency. As phase increases, the LFQPO frequency decreases (II and III), flattens (IV) and then increases again (V). It is very interesting that LFQPO frequency remains constant in the interval IV, and drops at $\phi = 0.92$ (Fig. 2c). As phase increases, the coherence of LFQPO increases rapidly (II), decreases quickly (III) and continues to decrease very slightly (IV, V and VI) (Fig. 2e).

3. Implications

In the ρ state, NRL11 showed that the energy spectrum has at least two components: the disk emission and the corona emission.

As phase increases, the LFQPO frequency decreases (II and III), flattens (IV) and then increases again (V) (Fig. 2c), while accretion disk radius increases continuously over the phase range 0.1 − 0.9, which covers intervals II, III, IV, and V (Fig. 7 in NRL11), suggesting that the LFQPO seems to be irrelevant to the accretion disk.

In the interval IV, which is covered by the slow rise of NRL11, both the LFQPO frequency and power-law index are relatively steady while the radius of the inner disk

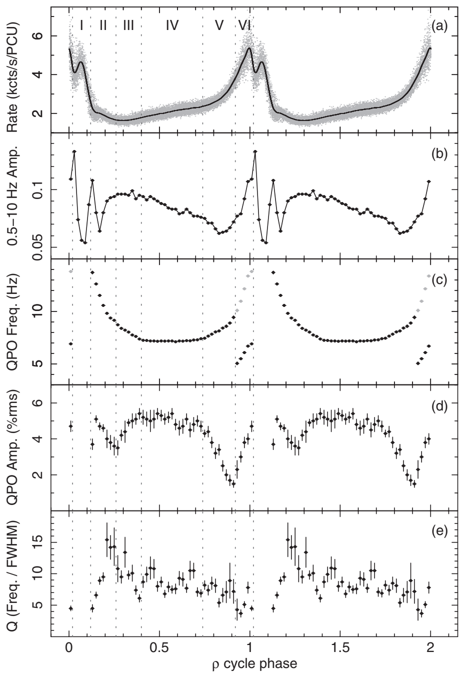

Figure 1. (a) The phase-folded PCA ρ class lightcurve in 2.0 − 37.8 keV band. (b) 0.5 − 10 Hz rms amplitude, (c) LFQPO frequency, (d) LFQPO amplitude, and (e) LFQPO coherence, as a function of ρ cycle phase.

https://doi.org/10.1017/S1743921312024891 Published online by Cambridge University Press

increases significantly (Fig. 2; Fig. 7 in NRL11). The fact that the LFQPO frequency and the power-law index remain relatively stable coincidentally indicates a possible correlation between the LFQPO and the corona.

There is no obvious LFQPO in the interval I, during which there is a hard pulse called by NRL11. NRL11 argued that some material collides with the hot corona after it has been ejected from the inner disk due to disk instability during the hard pulse phase. Based on the presumption that LFQPO is produced in the corona, the absence of LFQPO may be caused by the violent disturbance in the corona owing to the collision.

The LFQPO frequency decreases smoothly during intervals II and III, which cover NRL11's phase of the hard X-ray tail during which a short-lived jet is said to be produced. Then the jet seems independent with the LFQPO considering that it has no influence on the LFQPO frequency based on the smooth evolution of the LFQPO frequency.

The LFQPO frequency drops at $\phi = 0.92$ (Fig. 2c). NRL11 argued that the disk becomes unstable and the inner disk radius decreases rapidly after phase 0.9 due to radiation pressure. The drop in the LFQPO frequency might be another signal which indicates that the corona has been changed significantly.

In summary, it shows that the LFQPO likely originate from the corona.

Acknowledgements

This research used the archive data provided by GSFC. It is supported by 2009CB824800, KJCX2-YW-T09, Grant No. 200821164 and Grant No. LHXZ 200802.

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