High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
Proceedings IAU Symposium No. 346, 2019
L. M. Oskinova, E. Bozzo, T. Bulik & D. Gies, eds.

doi:10.1017/S1743921319001832

The possible origin of high frequency quasi-periodic oscillations in low mass X-ray binaries

ChangSheng Shi[1,2], ShuangNan Zhang[3,5,6] and XiangDong Li[2,4]

[1]College of Material Science and Chemical Engineering, Hainan University, Hainan 570228, China
email: shics@hainu.edu.cn

[2]Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210046, China

[3]Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

[4]Department of Astronomy, Nanjing University, Nanjing 210046, China;

[5]National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

[6]Physics Department, University of Alabama in Huntsville, Huntsville, AL 35899, USA

Abstract. We summarize our model that high frequency quasi-periodic oscillations (QPOs) both in the neutron star low mass X-ray binaries (NS-LMXBs) and black hole LMXBs may originate from magnetohydrodynamic (MHD) waves. Based on the MHD model in NS-LMXBs, the explanation of the parallel tracks is presented. The slowly varying effective surface magnetic field of a NS leads to the shift of parallel tracks of QPOs in NS-LMXBs. In the study of kilohertz (kHz) QPOs in NS-LMXBs, we obtain a simple power-law relation between the kHz QPO frequencies and the combined parameter of accretion rate and the effective surface magnetic field. Based on the MHD model in BH-LMXBs, we suggest that two stable modes of the Alfv́en waves in the accretion disks with a toroidal magnetic field may lead to the double high frequency QPOs. This model, in which the effect of the general relativity in BH-LMXBs is considered, naturally accounts for the 3:2 relation for the upper and lower frequencies of the QPOs and the relation between the BH mass and QPO frequency.

Keywords. accretion, accretion disks, MHD, X-rays: binaries.

1. Introduction

Quasi-periodic oscillations are a key phenomenon of variability in many X-ray binaries (XBs), such as neutron star low-mass X-ray binaries (NS-LMXBs), black hole low-mass X-ray binaries (BH-LMXBs) (see Strohmayer *et al.* 1996; van der Klis 2006), also in high mass X-ray binaries (James *et al.* 2010). Accretion from the companion star is a general phenomenon in those XBs and there is a certain relation between frequencies of QPOs and accretion rate. However, there does not exist a one-to-one relation between the kHz QPOs and the X-ray intensity in systems such as in 4U 1636–53 and 4U 1608–52. This interesting phenomenon is called "parallel tracks".

As a promising phenomenon to explore the general relativity effect, QPOs were widely studied in many models (e.g. Miller, Lamb & Psaltis 1998; Stella & Vietri 1999; Osherovich & Titarchuk 1999; Abramowicz & Kluźniak 2001, 2003; Erkut, Psaltis & Al-par 2008; Shi & Li 2009, 2010; Shi, Zhang & Li 2014, 2018). Both in NS-LMXBs and BH-LMXBs, some disturbance frequently emerges in an accretion disk because of

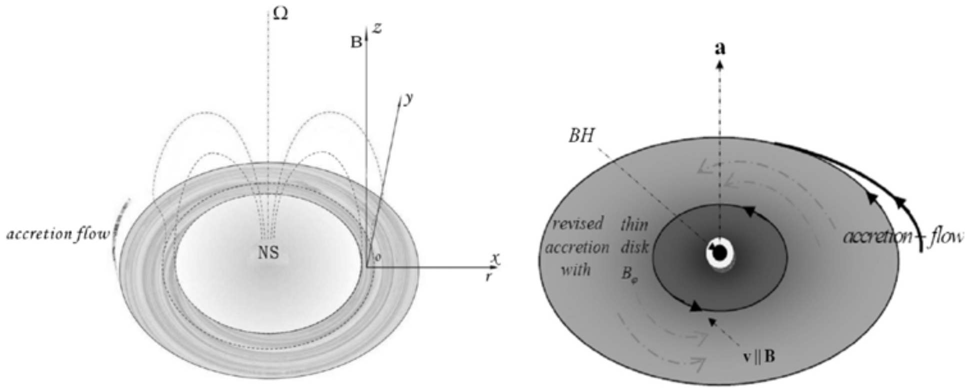

Figure 1. The sketch about an accretion process (Left: an accreting NS with a dipolar magnetic field; Right: an accreting BH with a toroidal magnetic field).

some instability and thus magnetohydrodynamic (MHD) waves are produced easily. We have solved fundamental dispersion equations and compared these frequencies with the frequencies of the QPOs in NS-LMXBs and BH-LMXBs. Then it is found that MHD waves are a promising origin of HFQPOs in LMXBs (Shi & Li 2009, 2010; Shi, Zhang & Li 2014, 2018).

2. NS-LMXBs and BH-LMXBs

As known to us, NSs are very different from BHs in many characteristics. (1) A NS has a rigid surface, which is effective to the release of gravitational energy of the accreted material, but a BH has not. (2) A NS has a dipolar magnetic field but a BH does not due to that any matter (including magnetic fields) can flow only into the event horizon. However, some weak toroidal magnetic field may emerge in the accretion disk that is rotating around the BH. Therefore, periodic pulses can be produced in a NS-XB but can not be found in a BH-XB and it is considered as a criterion to differentiate between a NS-XB and a BH-XB. Therefore the accretion matter can be funneled to the two poles by the magnetic field in NS-LMXBs but it does not happen in BH-LMXBs.

3. KHz QPOs in NS-LMXBs

Shi, Zhang & Li (2014, 2018) considered that MHD waves are generated at the magnetosphere radius and obtained the dispersion equations by solving a group of disturbing MHD equations in the accretion mode of NS-LMXBs. Then the modes of MHD waves from these disturbance are calculated and suggested to be the origin of the kilohertz quasi-periodic oscillations (kHz QPOs) in NS-LMXBs.

When the compressed magnetosphere is considered, the magnetic field is not a dipolar magnetic field (Shi, Zhang & Li, 2018). The nondipolar magnetic field can not be expressed as $B_{\rm NS}R^3$ but as $B_*R^3 = cB_{\rm NS}R^3$, where $B_{\rm NS}$ is the surface magnetic field for the non-deformation magnetosphere, B_* the effective surface magnetic field of a NS, c is a simple form factor, and R is the radius of a NS.

After calculating the frequencies of the MHD waves with different effective magnetic fields, the parallel tracks can be reproduced (Shi, Zhang & Li, 2018). When $\dot{M}/B_*^2$ as an integrated parameter is considered, the one-to-one relation between the frequencies and $\dot{M}/B_*^2$ is shown. Also, the similar relation was shown in Shi, Zhang & Li (2014). Namely the tracks for different B_* from all the data of kHz QPOs converge into a group of curves. Then we can test if the model and the frequencies of the twin kHz QPOs are the best parameters to describe these observational results. The variable instantaneous accretion rate as a important factor leads to the changing of kHz QPO frequency, and the shift of one track in "parallel tracks" originates from the slowly varying effective magnetic field.

4. HFQPOs in BH-LMXBs

Different from the model of kHz QPOs, we considered an inner advection-dominated accretion flow (ADAF) surrounded by an outer thin disk in the very high state of a BH-LMXBs (Shi & Li 2010). After the general relativistic magnetohydrodynamic equations of the perturbed plasma at the boundary between ADAF and the thin accretion disk (r_{tr}) have been solved, two stable modes of the Alfvén waves in the accretion disks with toroidal magnetic fields are obtained. The toroidal magnetic fields are widely believed to be generated by the dynamo mechanism. These two modes produced in the transition region (r_{tr}) are suggested to lead to the double high frequency QPOs. Then the velocities of the twin Alfvén waves in general relativity can be obtained and they can be converted as the same form with the expression of De Villiers & Hawley (2003) in the special relativity.

The ratio of the upper and lower frequencies between the calculated twin modes is very close to 3:2. Therefore the MHD waves with the ratio of the frequencies may be the promising origin of the HFQPO pairs. When the structure of the accretion disk with toroidal magnetic field (Begelman & Pringle 2007) is considered, the relation $\nu \propto M^{-1}$ can be obtained, where ν is the frequency of a HFQPO in BH-LMXBs and M is the mass of the BH. It is consistent with the observation of the QPO frequencies in the three BHs (GRO J1655−40, GRS 1915+105 and XTE J1550−56).

5. Discussion and conclusion

In many models, the kinematic frequency (e.g. the Kepler frequency) of orbital motion of hot spots and clumps is considered as one of the twin HFQPOs. Barret *et al.* (2005) measured the quality factor (Q) for the HFQPOs in 4U 1608−52, and found that Q $\sim$ 200. They believed that such high coherency is not possible to achieve from kinematic effects in orbital motion. However, in the axisymmetric, ideal magnetohydrodynamic simulation of Parthasarathy *et al.* (2017) for an oscillating cusp-filling tori orbiting a non-rotating neutron star, they considered different eigenmodes lead to the difference of the quality factor of the twin kHz QPOs. In our model, two different modes correspond to the twin HFQPOs and they may also lead to the difference of the quality factor as Parthasarathy *et al.* (2017) obtained, which is an important field to be explored next in the future.

As described above, the kHz QPOs in NS-LMXBs and the HFQPOs in BH-LMXBs may both be produced from MHD waves in the certain accretion process. However, the different magnetic fields and accretion processes lead to different results. In a word, the MHD waves (including Alf́ven waves) are therefore a promising origin.

References

Abramowicz, M. A., Bulik, T., Bursa, M., & Kluźniak, W. 2003, *A&A*, 404, L21
Abramowicz, M. A., & Kluźniak, W. 2001, *A&A*, 374, L19
Barret, D., Kluźniak, W., Olive, J. F., Paltani, S., & Skinner, G. K. 2005, MNRAS, 357, 1288
Begelman, M. C., & Pringle, J. E. 2007, MNRAS, 375, 1070
De Villiers, J. P., & Hawley, J. F. 2003, *ApJ*, 589, 458
Erkut M. H., Psaltis D., Alpar M. A. 2008, *ApJ*, 687, 1220
James, M., Paul, B., Devasia, J., & Indulekha, K. 2010, MNRAS, 407, 285
Li, X.-D., & Zhang, C.-M. 2005, *ApJL*, 635, L57
Miller, M. C., Lamb, F. K., & Psaltis, D. 1998, *ApJ*, 508, 791
Osherovich, V., & Titarchuk, L. 1999, *ApJL*, 522, L113
Parthasarathy V., Kluźniak W., Čemeljić M. 2017, MNRAS, 470, L34

Shi, C.-S. 2011, *Research in Astronomy and Astrophysics*, 11, 1327
Shi, C.-S., & Li, X.-D. 2010, *ApJ*, 714, 1227
Shi, C.-S., Zhang, S.-N., & Li, X.-D. 2014, *ApJ*, 791, 16
Shi, C. 2010, *Science China Physics, Mechanics, and Astronomy*, 53, 247
Shi, C., & Li, X.-D. 2009, *MARAS*, 392, 264
Stella, L., & Vietri, M. 1999, *Physical Review Letters*, 82, 17
Strohmayer, T. E., Zhang, W., Swank, J. H., *et al.* 1996, *ApJL*, 469, L9
van der Klis, M. 2006, in: W. Lewin & M. van der Klis (eds.), *Compact stellar X-ray sources*, Cambridge Astrophysics Series No. 39 (Cambridge, UK: Cambridge University Press), p. 39
Zhang, C. 2004, *A&A*, 423, 401

https://doi.org/10.1017/S1743921319001832 Published online by Cambridge University Press