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The kHz QPOs of Neutron Stars and Millisecond Pulsars and Implications

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Abstract. The kilohertz quasi-periodic oscillations (kHz QPOs) have been found in neutron star low mass X-ray binaries (NS-LMXBs), which present the millisecond timing phenomena close to the surface of the compact objects. We briefly summarize the following contents: (1). The correlations and distributions of twin kHz QPOs; (2). The relations of high-low frequency QPOs; (3). The QPO properties of NS Atoll and Z sources; (4). No clear direct correlations between NS spins and QPOs; (5). The mechanisms of kHz QPOs; (6). The implications of kHZ QPOs, e.g., NS mass and radius, disk thickness and magnetic field of Atoll and Z source.

Keywords. Low mass X-ray binary, neutron star, accretion discs

1. Introduction

The kHz QPOs in NS-LMXBs were firstly discovered in 1996 in both Atoll and Z sources (Hasinger and van der Klis 1989) since the launch of RXTE in the end of 1995 (van der Klis 2000, 2006). Although RXTE has finished its destination journey, the data of RXTE are still coming out for analysis. The QPO have been found in about 40 NS-LMXBs, where 28 sources are found the twin kHz QPOs, which are believed to be the millisecond oscillations around the surface of compact objects, thus kHz QPO observations provide us a powerful tool to probe the strong gravity regimes of compact objects (van der Klis 2006, 2008). Through kHz QPO explorations, we could know the properties of Keplerian motion or Einstein gravity near compact objects, and infer the mass, radius and magnetic field of NS, and the accretion flow and magnetosphere of NS. We can understand the details of formation process of millisecond pulsar while NS is recycled in the accretion system (Alpar *et al.* 1982; Chakrabarty & Morgan 1998). Furthermore, kHz QPOs will help us the general properties of accretion physics in binary compact systems (Bhattacharya & van den Heuvel 1991; Tauris *et al.* 2012; Liu Q.Z. *et al.* 2007; van den Heuvel 2004; Shore *et al.* 2010).

2. Brief Summary of kHz QPOs

Correlations and distributions of twin kHz QPOs Now, it is clear that the frequencies of twin kHz QPOs follow a non-linear relation, or in other words the constant ratio or beat with the spin frequency for the twin QPOs cannot work (Belloni *et al.* 2007). Twin kHz QPOs (upper ν_2 and lower ν_1) show a power law relation (Zhang *et al.* 2006). The linear correlation between HBO and lower kHz QPO has been reported, which can be extended to black hole or even white dwarf binary systems (Belloni *et al.* 2002, 2005, Psaltis *et al.* 1999). Like Cir X-1, all QPO data seem to follow a parabola route in the plot of difference of twin QPOs ($\Delta\nu = \nu_2$ - ν_1) vs. upper frequency (ν_2). However, for the individual Atoll or Z source, the kHz QPOs are usually detected in the frequency regime of high frequency, e.g. from 500 Hz - 1200 Hz. This correlation leave a strong constrain on the QPO models. At present, only two models can predict this parabola trend, the relativistic precession model (RPM) by Stella and Vietri (1999) and Alfven wave oscillation model (AWOM) by Zhang (2004). In RPM, the free parameter of model is NS mass, which are often overestimated by kHz QPO data to be about 2 solar masses, a bigger value than the averaged value (1.6 solar mass) of millisecond pulsars (MSPs) (Zhang *et al.* 2011). In AWOM model, the free parameter is the mass density of star, which is consistent with the standard value of NS with 1.4 solar mass and 15 km.

The distinction of QPO and spin frequency of Atoll and Z sources. Averagely, the maximum kHz QPO frequency of Atoll is a slight bigger than that of Z sources, and the reason for this may be the thickness of accretion disk, e.g. the disk of Z source should be thicker than that of Atoll, which would be also the reason why the spin frequencies have not yet been detected in Z sources. Moreover, the size of corona of Z source would be bigger than that Atoll, where a lot of emission photons should be blocked there.

Q-factors of twin kHz QPOs. The Q-factor properties of Atoll and Z sources are complicated Barret *et al.* 2011, Méndez 2006). Our statistics seems to infer a rough correlation for the Q-factors of upper and lower kHz QPOs to the accretion rate (Wang *et al.* 2011), and the implied mechanisms for upper and lower should be different. The smaller averaged Q-factor of Z sources than that of Atolls should be ascribed to the thicker disks of Z sources (or corona size), and the quantitative work on this point is going on. The abrupt changing of Q-factors at some frequency seems to concorde to the changing of twin kHz QPO correlation, however that the physics behind is ascribed to ISCO or particular radius has not yet been determined clearly.

The mechanisms of kHz QPOs It has been long time debates on the mechanisms of kHz QPOs. Abramowicz *et al.* (2003) wish to consider the relativistic disk oscillations for QPO productions at preferred radius, which can be applied to 3:2 QPO ratios of BHs, but not for NS QPO ratio that has no a constant ratio of 3:2. The simple beat model cannot fit for the twin kHz QPO data with the detected spin frequency (Miller *et al.* 1998). The relativistic precession model (RPM) by Stella and Vietri (1999) ascribes the upper to Keplerian orbital frequency of disk matter and the lower to the relativistic perihelion precession frequency of accreting matter. By exploiting this model, we compare the twin kHz QPOs of Sax J 1808.4-3658 (Wijnands *et al.* 2003) with the model prediction, and prefer the NS mass of this source is about 3.2 solar mass, a upper limit of NS mass before collapsing to BH, which is much bigger than its estimated mass of 1.4 solar mass. Thus, RPM should overcome the overestimation of NS mass. In Alfven wave oscillation model (AWOM, Zhang 2004, Zhang *et al.* 2007b, 2009), the upper is also considered as the Keplerian orbital frequency, and the lower is ascribed to the Alfven wave Oscillation frequency of accreting matter along the orbit with magnetic field. We once again apply AWOM model to Sax J 1808.4-3658, and find that its NS radius is about 20 km for the mass of 1.4 solar mass. NS radius of 20 km is bigger than what we often presumed 15 km, then this value has no contradiction to the predictions of nuclear physics or from other arguments (Lattimer & Prakash 2004; Menezes *et al.* 2004; Haensel *et al.* 2007).

The implications of NS mass and radius, NS magnetic field NS mass and radius can be inferred by the highest kHz QPO frequency, by considering it as a Keplerian frequency at NS surface or ISCO. The QPO models, e.g. RPM or AWOM, can also prefer NS mass or its mass density (M/R^3), based on which we can compare the EOS of nuclear matter (Miller 2002; Ozel 2006; Haensel 2007, 2008). Although the luminosity values of Atoll and Z are very different, perhaps spanning 2 magnitudes, then the similar kHz QPO distributions of them inferred that both sources share the similar magnetosphere, which infers a 10 times stronger field of Z source (Eddington luminosity) than that of Atoll (0.01 Eddington luminosity). To interpret the Atoll and Z changing in Cir X-1 and XTE 1701, our arguments are below: while the luminosity is strong (weak), then the source shows a Z state (Atoll), since a strong luminosity (high accretion rate) will correspond to a stronger field (inward the magnetosphere).

3. Perspective of kHz QPOs

The maximum QPO frequency may show the surface information of NS, by which we can com=nstrain the NS radius and mass. The 1200 Hz often gives the loose constrains of NS parameters, then this frequency may occur at some preferred radius or barrier of magnetosphere-disk before the accreting matter colliding the NS surface or ISCO. 1860 Hz has been reported, but such a high frequency may be a harmonic of 900 Hz (Bhattcharyya 2011). The area of deep inside magnetosphere-disk may absorbs and blurs the emission QPO photons, which can destroy or weaken the QPO signal below our detection limit. In any cases, we can employ the maximum QPO frequency to explore the inner structure of accretion disk. The HBO mechanism is not clear. If it is considered as a similar mechanism to the lower kHz QPO but occurred at a far radius, or outer boundary of disk, then it should be 50 km for a kHz QPO production at 20 km. However, the origin of outer disk radii need more through study. The spin and kHz QPOs has no direct correlations, then the rough indirect correlations may be possible, since averaged kHz QPO frequency seems to be proportionally related to spin frequency, which needs the further quantitative statistics.

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References

Abramowicz, M. A. *et al.* 2003, *A&A*, 404, L21
Alpar, M. A., Cheng, A. F., Ruderman, M. A., *et al.* 1982, *Nature*, 300, 728
Bhattacharyya, S. 2010, *Research in Astronomy and Astrophysics*, 10, 227
Bhattacharya, D., & van den Heuvel, E. P. J. 1991,*Phys. Rep*, 203, 1
Barret, D., Boutelier, M., & Miller, M. C. 2011, *ApJ*, 728, 9
Belloni, T., Psaltis, D., & van der Klis, M. 2002, *ApJ*, 572, 392
Belloni, T., Méndez, M., & Homan, J. 2005, *A&A*, 437, 209
Belloni, T., Méndez, M., & Homan, J. 2007, *MNRAS*, 376, 1133
Chakrabarty D., Morgan, E. H. 1998, *Nature*, 394, 346
Haensel, P., Potekhin, A. Y., & Yakovlev, D. G. 2007, Neutron Stars: Equation of State and Structure, Springer and Berlin
Haensel, P., Zdunik, J., & Bejger, M. 2008, *New Astronomy Review.*, 51, 785
Hasinger, G. & van der Klis, M. 1989, *A&A*, 225, 79
Lattimer, J. M. & Prakash, M. 2004, *Science*, 304, 536
Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2007, *A&A*, 469, 807
Méndez, M. 2006, *MNRAS*, 371, 1925
Menezes *et al.* 2006, *Phys. Rev. C*, 73, 025806
Miller, C. 2002, *Nature*, 420, 31
Miller, M. C., Lamb F. K., Psaltis D., 1998, ApJ, 508, 791
Özel, F. 2006, *Nature*, 441, 1115
Psaltis, D., Belloni, T., & van der Klis, M. 1999, *ApJ*, 520, 262
Stella, L. & Vietri, M. 1999, *Phys. Rev. Lett.*, 82, 17
Tauris, T. M., Langer, N., & Kramer, M. 2012, *MNRAS*, 425, 1601
Shore, S. N., Livio, M., & van den Heuvel, E. P. J. 2010, Interacting Binaries, Springer-Verlag
van den Heuvel, E. P. J. 2004, *Science*, 303, 20
van der Klis, M. 2000, *ARAA*, 38, 717

van der Klis, M. 2006, in Lewin, W. H. G., van der Klis M., eds, Compact Stellar X-Ray Sources, Cambridge Univ. Press, Cambridge, p. 39

van der Klis, M. 2008, in Wijnands R. *et al.*, eds, A Decade of Accreting Millisecond X-Ray Pulsars, AIP Conf. Ser. Vol. 1068. Am. Inst. Phys., Melville, NY, p. 163

Wang, J., Zhang, C. M., Zhao, Y. H. *et al.* 2011, *A&A*, 528, 126

Wijnands R. *et al.*, 2003, Nature, 424, 44

&Zhang, C. M., 2004, *A&A*, 423, 401

Zhang, C. M., Yin, H. X., Zhao, Y. H. *et al.* 2006, *MNRAS*, 366, 1373

Zhang, C. M., Yin, H. X., Kojima, Y. *et al.* 2007a, *MNRAS*, 374, 232

Zhang, C. M., Yin, H. X., Zhao, Y. H. *et al.* 2007b, *AN*, 328, 491

Zhang, C. M. 2009, *AN*, 330, 398

Zhang, C. M., Wang, J., Zhao, Y. H. *et al.* 2011, *A&A*, 527, 83


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