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Some Conclusions on the MHD Alfvén Wave Oscillation Model of kHz QPO

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Abstract MHD Alfvén wave oscillation for the interpretation of the twin kilohertz Quasi Periodic Oscillations (kHz QPOs) of X-ray spectra of Low Mass X-Ray Binaries (LMXBs) is proposed, and the upper kHz QPO frequency coincides with the Keplerian frequency. The model concludes that the kHz QPO frequencies inversely depend on the disk radius, and the theoretical relation between the upper frequency (ν_2) and the lower frequency (ν_1) is $\nu_1 \sim \nu_2^2$, which is similar to the measured empirical relation. The separation between the twin frequencies decreases (increases) with increasing the kHz QPO frequency if the lower kHz frequency is more (less) than $\sim$400 Hz.

Key words: X–rays: accretion disks — stars: neutron — X–rays: stars

1 INTRODUCTION

Rossi X-ray Timing Explorer (RXTE) led to the discovery of Quasi Periodic Oscillations (QPOs) in their X-ray brightness, with frequencies $\sim 10^{-1} - 10^3$ Hz (see van der Klis 2000, 2004 for a recent review). Thereafter, the kHz QPO mechanism of LMXB has been paid much attention, however the proposed models are still far from explaining all detected data. The Z sources (Atoll sources), which are high (less) luminous NS LMXBs (Hasinger & van der Klis 1989), typically show four distinct types of QPOs (van der Klis 2000). At present, these are the normal branch oscillation (NBO) $\nu_{\rm NBO} \simeq 5 - 20$ Hz, the horizontal branch oscillation (HBO) $\nu_{\rm HBO} \simeq 10 - 70$ Hz, and the kHz QPOs $\nu_2(\nu_1) \simeq 300 - 1300$ Hz that typically occur in pairs in more than 20 sources, upper frequency ν_2 and lower frequency ν_1. In 11 sources, nearly coherent burst oscillations $\nu_{\rm burst} \simeq 270 - 620$ Hz have also been detected during thermonuclear Type I X-ray bursts, which are considered as the NS spin frequencies ν_s or twice of them (see, e.g., Strohmayer et al. 1996; Strohmayer and Bildsten 2003). All of these QPOs but the burst oscillations have centroid frequencies that increase with the inferred mass accretion rate $\dot{M}$. Furthermore, the frequencies ν_2 and ν_1, as well as the frequencies ν_2 and $\nu_{\rm HBO}$, follows very similar relations in five Z sources, and the QPO frequencies of LMXBs and the black hole candidates (BHC) follow a tight and systematical correlation over three orders of magnitude in frequency (Psaltis et al. 1998, 1999; Belloni et al. 2002). Nonetheless, the frequency separation decreases systematically with instantaneous $\dot{M}$, e.g., Sco X-1 (van der Klis et al. 1997), 4U1608−52 (Mendez et al. 1998a,b), 4U1735-44 (Ford et al. 1998) and 4U1728−34 (Mendez &

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van der Klis 1999), which seems to make the simple beat model (Miller et al. 1998) inadequate except the further arguments proposed. Subsequently, the high frequency QPOs have been detected in the black hole candidates, which can be used as a probe of relativistic effect in the strong gravity regime (see, e.g., van der Klis 2004, 2000; Cui et al 1998; Zhang 1997).

The various theoretical models have been proposed to account for the QPO phenomena in X-ray binaries (review see, e.g., Psaltis 2000), such as the beat model (Strohmayer et al. 1996; Miller et al. 1998; Miller 2004), the general relativistic precession model (Stella & Vietri 1999; Stella et al. 1999; Psaltis & Norman 2000; Vietri & Stella 1998), which can satisfactorily explain the varied kHz QPO separation $\Delta\nu$, the transitional layer disk model (see, e.g., Titarchuk et al 1998; Titarchuk & Osherovich 2000), the nonlinear disk resonance model by Abramowicz et al. (2003), as well as the diskseismic model (see, e.g., Wagoner 1999), there has not yet been any model satisfactorily to explain all observed QPO phenomena of LMXBs until now. The mechanisms of kHz QPOs of accreting X-ray binaries are still debated and open problems.

The paper is organized as follows. In Sect. 2, the MHD Alfvén wave oscillation model (AWOM) is described, and its predictions and comparisons with the well detected sample sources are plotted in the figures. The conclusions and consequences of the model are discussed in the final section.

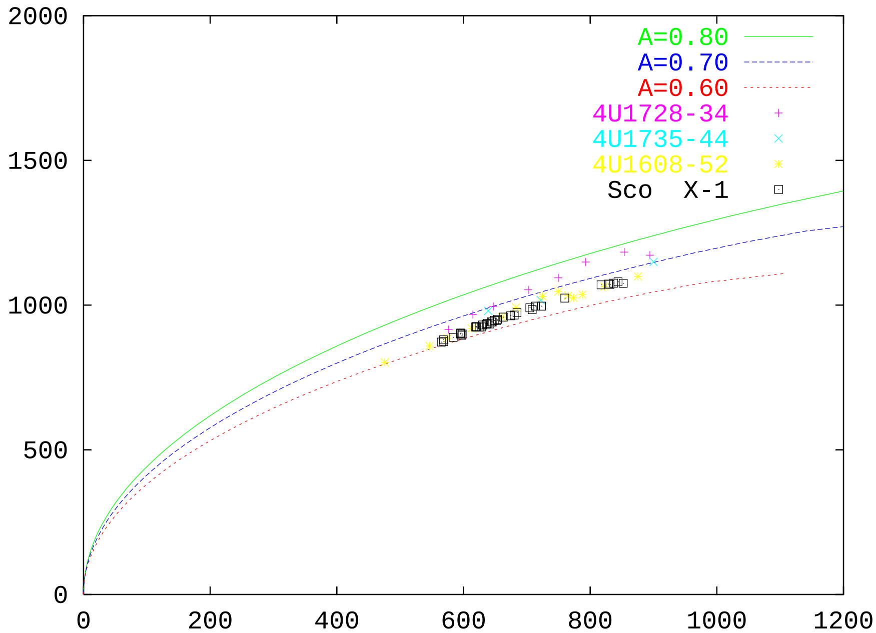

Fig. 1 ν_2 versus ν_1 plot. The horizontal axis is the lower kHz QPO frequency ν_1 and the vertical axis is the upper kHz QPO frequency ν_2. The kHz QPO data of four detected sample sources are plotted. The model presents a well consistence with the measured data for the NS averaged mass density parameters A=0.6, 0.7 and 0.8, which are shown in the three theoretical curves from bottom to top.

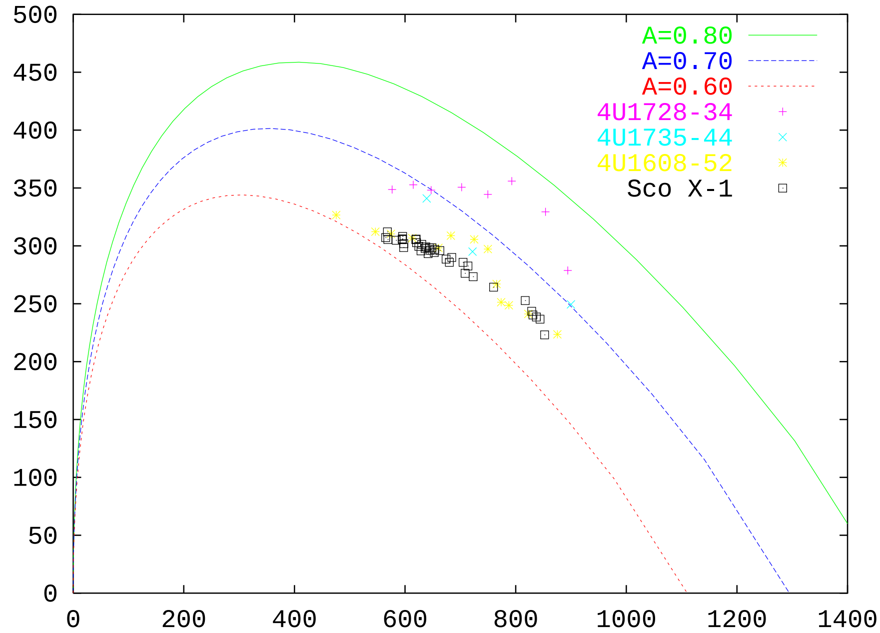

Fig. 2 $\Delta\nu$ versus ν_1 plot. The horizontal axis is the lower kHz QPO frequency ν_1 and the vertical axis is the twin kHz QPO frequency separation $\Delta\nu$. The kHz QPO data of four detected sample sources are plotted. The model presents a well consistence with the measured data for the NS averaged mass density parameters A=0.6, 0.7 and 0.8, which are shown in the three theoretical curves from bottom to top.

2 THE MODEL

While the mechanisms responsible for the twin kHz QPOs in LMXBs are still uncertain, we associate them with the Alfvén wave oscillation frequencies (AWOFs) at a certain preferred radius, where the AWOF with the spherical accretion mass density coincides with the Keplerian orbital frequency $\nu_{\rm K}$ and the AWOF with the polar accretion mass density is lower than $\nu_{\rm K}$ except on the surface of star. As a phenomenological prescription, these two AWOFs are interpreted to account for the upper kHz QPO ν_2 and the lower kHz QPO ν_1, respectively. As a preliminary investigation of kHz QPO mechanisms, we are not concerned with the actual mechanisms by which kHz QPOs in the X-ray fluxes of LMXBs may be produced (see, e.g., Miller et al. 1998; Psaltis 2000; van der Klis 2000 for extensive discussion on various possibilities). Rather, our main purpose is to stress the consistence between the model and the measured kHz QPO data to arise the further understanding of the behavior of accretion flow in LMXBs, and leave the mechanism possibility arguments in the discussion forum of the final section.

At some preferred radius r of accretion disk, where the azimuthal magnetic field is comparable to the unperturbed dipole magnetic field in the equatorial plan (Shapiro & Teukolsky 1983), so we take the azimuthal component of field to be equal in magnitude to the dipole field in the later calculations. So, the Alfvén velocity $v_{\rm A}$ is,

$$v_{\rm A}(r) = \frac{B(r)}{\sqrt{4\pi\rho}}\,, \tag{1}$$

where $B(r) = B_s(R/r)^3$ and B_s are the dipole magnetic field strengths at the radius r and at the surface of star with the radius R, respectively. Therefore, the Alfvén wave oscillation frequency $\nu_{\rm A}$ can be calculated by

$$\nu_{\rm A}(r) = \frac{v_{\rm A}(r)}{2\pi r} = \frac{B_s(R/r)^3}{2\pi r}\sqrt{\frac{Sv_{\rm ff}}{4\pi \dot{M}}} \propto \sqrt{S}\,, \tag{2}$$

where the mass density of the accreted matter $\rho = \dot{M}/[Sv_{\rm ff}]$ (Shapiro & Teukolsky 1983) is applied with the accretion rate $\dot{M}$, the free fall velocity $v_{\rm ff} = \sqrt{2GM/r} = c\sqrt{R_s/r}$, where $R_s = 2GM/c^2$ is the Schwarzschild radius and can be expressed as $R_s \simeq 3m(\rm km) = 0.3m(10\,km)$ with $m = \frac{M}{M_\odot}$, the NS mass in unit of solar mass, and the area S representing the spherical area S_r or the polar cap area S_p, which are constrained by the radius r and expressed, respectively,

$$S_r = 4\pi r^2\,, \tag{3}$$

$$S_p = 4\pi R^2(1-\cos\theta_c)\,,\ \sin^2\theta_c = R/r \equiv X\,, \tag{4}$$

where θ_c is the open angle of the last field line to close at radius r. As an approximation, the polar cap area is usually written as $S_p = \frac{2\pi R^3}{r}$ if $R \ll r$ (Shapiro & Teukolsky 1983). For simplicity, it is convenient to write the two areas by means of the scaled radius parameter $X \equiv R/r$,

$$S_r = 4\pi R^2 X^{-2}\,,\ S_p = 4\pi R^2(1-\sqrt{1-X})\,. \tag{5}$$

It is assumed that the upper and the lower kHz QPO frequencies are from the MHD Alfvén wave oscillations with the different accreted material mass densities, corresponding to the different areas S_r and S_p respectively. The Alfvén wave oscillation frequency with the spherical mass density coincides with the Keplerian frequency, therefore,

$$\nu_2 = \sqrt{\frac{GM}{4\pi^2 r^3}} = \nu_A(S_r) = 1850({\rm Hz})AX^{3/2}\,, \tag{6}$$

with the parameter A defined as $A = (m/R_6^3)^{1/2}$ and $R_6 = R/10^6\,$cm, or equivalently expressed as,

$$R_6 = 1.27m^{1/3}(A/0.7)^{-2/3}\,(10\,{\rm km}). \tag{7}$$

The physical meaning of A is clear that A^2 represents the measurement of NS averaged mass density. So, by means of Eq.(2) with the correlation $\nu_A \propto \sqrt{S}$, we have the lower kHz QPO frequency,

$$\nu_1 = \nu_A(S_p) = \nu_2\sqrt{S_p/S_r} = \nu_2 X\sqrt{1-\sqrt{1-X}}\,. \tag{8}$$

The twin kHz QPO frequencies only depend on the two variables, the parameter A and the scaled radius X=R/r, so these two variables can be implied if the twin kHz QPO frequencies are simultaneously detected. Therefore, the ratio of twin frequencies is easily obtained, by setting $y(X) = \frac{\nu_2}{\nu_1}$,

$$\frac{\nu_1}{\nu_2} = y^{-1}(X) = X\sqrt{1-\sqrt{1-X}}\,, \tag{9}$$

which is independent of the parameter A and is only related to the parameter X. Furthermore, the twin frequency separation is given as follows,

$$\Delta\nu \equiv \nu_2 - \nu_1 = \nu_2(1 - X\sqrt{1-\sqrt{1-X}})\,. \tag{10}$$

The comparisons of the model to the detected data of four X-ray sources (4U1608−52, 4U1735−44, 4U1728−34 and Sco X-1) are listed in figures. The relations ν_2 versus ν_1 and $\Delta\nu$

versus ν_1 are plotted in FIG. 1 and FIG. 2, respectively, together with the well measured four samples, and they show that the agreements between the model and the observed QPO data are quite well for the selected ranges of the NS parameters A=0.6, 0.7 and 0.8. In FIG. 1, we find that the tendencies of the observed data points are very similar and systematically steeper than the theoretical expectations, which means that the neutron star parameters other than the averaged mass density parameter A will effect, but at moment our simple model has not yet added many neutron star realistic contributions, such as the modifications from the rotational effect and the possible star magnetic structure, etc. The considerations of these factors will construct our subsequent work. In FIG. 2, we find that $\Delta\nu$ increases with increasing ν_1 if $\nu_1 < 408$ (A/0.7) Hz and $\Delta\nu$ decreases with increasing ν_1 if $\nu_1 > 408$ (A/0.7) Hz. The theoretical relation between the twin frequencies is derived from Eq.(6) and Eq.(8),

$$\nu_1 = 629(\mathrm{Hz})A^{-2/3}\nu_{2k}^{5/3}\sqrt{1-\sqrt{1-(\frac{\nu_{2k}}{1.85A})^{2/3}}}\,, \tag{11}$$

where $\nu_{2k} = \nu_2/(1\,\mathrm{kHz})$. If $\nu_2 \ll 1850A(\mathrm{Hz}) = 1295(\frac{A}{0.7})(\mathrm{Hz})$, so we have the approximated theoretical relation between the twin frequencies,

$$\nu_1 = (382/A)(\mathrm{Hz})\nu_{2k}^2 = 546(\mathrm{Hz})(\frac{A}{0.7})^{-1}(\nu_{2k})^2\,. \tag{12}$$

The similar $\nu_1 - \nu_2$ empirical correlation has also been found for the measured kHz QPO sources (see, e.g., Stella et al. 1999; Psaltis et al. 1998; Psaltis 2000; Psaltis and Norman 2000).

3 DISCUSSIONS AND CONCLUSIONS

The proposed MHD Alfvén wave oscillation model (AWOM) for kHz QPO in LMXBs has shown that the consistence between the model and the detections. While the dynamic details of the mechanisms responsible for the kHz QPOs in LMXBs are still uncertain, so it is convenient to associate them with the MHD Alfvén wave oscillations at a certain preferred radius, a quasi sonic-point radius for instance, where the MHD tube loop may be formed to duct the accreted matter onto the polar cap of star. It is imagined that this preferred radius is a critical or a transitional radius at where the spherical accretion matter with the low mass density is transferred into the high mass density to follow the loop to join the accreting neutron star. The critical transition would arise MHD turbulence to liberate much more energy than that at other positions. The twin QPOs are inversely related to the radii, so the increase of the accretion rate will result in the increase of QPO frequencies. The homogeneous distribution of the detected kHz QPO in Z sources (high mean accretion rate) and Atoll sources (low mean accretion rate) (van der Klis 2000; Psaltis et al. 1999; Belloni et al. 2000) reveals that both sources have the similar geometry scales in the magnetospheres. In our model $\Delta\nu$ increases with increasing ν_1 if $\nu_1 < 360(A/0.7)$ Hz and $\Delta\nu$ decreases with increasing ν_1 if $\nu_1 > 360(A/0.7)$ Hz. Moreover, in this simple phenomenological model we have not yet figured out the excitation and damping mechanisms of Alfvén wave oscillation and how they modulate the X-ray flux responsible for the productions of kHz QPOs, and the relevant researches have been paid attentions recently by Rezania and Samson (2005) and Rezania et al (2004).

As a conclusion, it is remarked that the model described here is simply and roughly one, and many physical details are neglected. As discussed, if the model were successfully to explain the observed QPOs in LMXBs, we can determine or constrain the NS mass and the radius by the kHz QPOs. In order to cover many detected QPO phenomena, we still have a tough investigation to explore.

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