Production of QPOs in Accreting Neutron Star Systems

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Abstract

Kilohertz QPOs have been detected from more than twenty neutron stars in low-mass X-ray binaries. Several different ideas have been proposed for their generation, involving resonances, magnetic interactions, and sharp transitions in the accretion flow. We show that although details are uncertain at this time, it is clear that the stellar magnetic field has a dynamic influence on the accretion flow. We also discuss the inferences about dense matter and strong gravity that can be drawn from all models, and the qualitative advances expected with a future high-area X-ray timing mission.

Key words: Stars: neutron, X-rays: binaries, X-rays: bursts, Relativity

1 Introduction

One of the goals of X-ray astronomy is to observe sources in extreme physical regimes, because these can help elucidate physics at the frontier. The discovery with the *Rossi* X-ray Timing Explorer (RXTE) of kilohertz quasi-periodic brightness oscillations (kHz QPOs) from neutron stars fits perfectly in this category. Their frequencies indicate that they must be generated very close to the neutron star, hence they can tell us about strong gravity and possibly the properties of the dense matter in the cores of such stars.

The precise implications, however, are not certain at this point because they vary somewhat depending on the model used to interpret the QPOs. There are, nonetheless, points of agreement that allow relatively robust conclusions to be drawn.

Here we evaluate the current state of modeling of kHz QPOs, and the resulting implications for strong gravity and dense matter. In § 2 we discuss the spin frequencies observed from a number of neutron star low-mass X-ray binaries (NS LMXBs). In § 3 we examine the current data for kHz QPOs, and in § 4 we discuss these in the context of resonances. We conclude in § 5 by discussing the model-independent conclusions that can be drawn from the current data, and the contributions that would be made by a future X-ray timing mission.

2 Neutron Star Spin Frequencies in LMXBs

One advantage of neutron star LMXBs compared with black hole LMXBs is that for many systems there is a known frequency: the stellar spin frequency. This gives us a fixed point to relate to various other frequencies in the system. There are two general spin-related phenomena that we now discuss: accretion-powered millisecond pulsars and oscillations from thermonuclear X-ray bursts.

2.1 Accretion-powered millisecond pulsars

Although as early as 1996 the discovery of high quality factor brightness oscillations from thermonuclear X-ray bursts (see below) convinced most people of their spin-related origin, all doubt was removed in 1998 with the detection of millisecond pulsations in the accretion-powered emission of the transient source SAX J1808–3658 (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998). This source was also detected later with RXTE, and as discussed below it provides a definitive link between stellar spin, thermonuclear burst oscillations, and kHz QPOs. There are now a total of six known accretion-powered millisecond pulsars (for a recent review, see Wijnands 2005). Interestingly, all six sources are transients, and three of them have orbital periods in the 40-44 minute range. It is not clear at this time what these facts imply.

2.2 Thermonuclear Burst Oscillations

Most of the information we have about spin frequencies in neutron star LMXBs comes from brightness oscillations during thermonuclear bursts that last a few seconds. These were discovered just a few months after the launch of RXTE (Strohmayer et al. 1996), and their quality factors $Q \equiv \nu/\mathrm{FWHM} \sim 1000$ and consistency of frequency between bursts of a given source convinced most researchers that the oscillations were due to rotational modulation of flux asymmetries on the star. We now have clear evidence of this in the millisecond pulsars SAX J1808–3658 (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998) and XTE 1814–338 (Strohmayer et al. 2003), where the oscillation frequency from normal bursts is essentially identical to the previously inferred spin frequency. In addition, a burst brightness oscillation was seen during an 800 second span of a "superburst" from 4U 1636–536 (Strohmayer & Markwardt 2002). When orbital Doppler shifts are included, the quality factor of the oscillation is in excess of 4×10^5. This is strongly indicative of a phenomenon related to the spin.

There do remain some puzzles about the details of the phenomenon. For example, most burst oscillations show a rise in frequency of a few Hertz near the beginning of the burst, and in "hot spot" models it is unclear how there would continue to be significant modulation after several seconds, when one might have expected that cooling would have reduced the amplitude significantly. Some of these issues might be addressed by nonradial oscillation models (e.g., Piro & Bildsten 2005), in which for a weakly magnetic star the burst oscillation frequency differs from the spin frequency by a few Hertz. It is also not yet clear whether there are important qualitative differences between burst oscillations from accretion-powered millisecond pulsars and from non-pulsars; Piro & Bildsten (2005) list several differences (e.g., that the frequency rise is faster in pulsars), but these may only be quantitative differences, and with only two pulsars that show burst oscillations their properties as a class are uncertain. In any case, it is now clear that the burst oscillation frequencies are very close to the spin frequencies, if not identical.

2.3 Distribution of LMXB spin frequencies

In the past, many researchers (including myself) have argued that many burst oscillation sources display pulsations at twice their spin frequency. If true, this would imply that spin frequencies cluster around ~ 300 Hz, and this line of thought led to explorations of gravitational radiation as a mechanism that would cause clustering of spin frequencies (e.g., Bildsten 1998; Andersson 1998; Ushomirsky et al. 2000). However, the analysis of SAX J1808–3658, which has a burst oscillation frequency of 401 Hz, showed that any persistent oscillations at half this frequency had at most 0.5% of the dominant amplitude (Wijnands et al. 2003), arguing strongly that the burst oscillation in this source (and by extension in all sources) is at the spin frequency. This suggests a reexamination of the spin frequency distribution for LMXBs.

Following the approach of Chakrabarty et al. (2003), we consider only those sources for which we have a fairly precise measurement of the spin, that is, those for which we see accretion-powered millisecond pulsations or thermonuclear burst oscillations. There are now 18 such sources. These range in frequency from 45 Hz (EXO 0748–676; Villarreal & Strohmayer 2004) to 620 Hz (4U 1608–52; see, e.g., Muno 2002), and there is no particular evidence of clustering. However, as emphasized by Chakrabarty et al. (2003), there is no instrumental bias against detecting much higher frequencies, so the lack of sources with $\nu_{\rm spin} > 620$ Hz is significant.

To estimate how significant, we can use standard likelihood-based techniques. For example (details in preparation), we consider a model in which the frequencies are distributed such that the probability of a source between frequencies ν and $\nu + d\nu$ is proportional to ν^x, with some upper cutoff frequency $\nu_{\rm cut}$. We find that the best power is $x \approx 0.8$, so there is a slight excess of sources at higher frequencies. We also find, consistent with Chakrabarty et al. (2003), that $\nu_{\rm cut} < 750$ Hz based on the current sample.

What do these results mean? A natural and probably correct interpretation of the lack of high-frequency sources is that there is a braking torque that limits their spin-up. For example, magnetic torques are consistent with the data if typically $B \sim 10^8$ G, and are also consistent with the $P - \dot{P}$ distribution of millisecond rotation-powered pulsars (for a recent discussion, see Andersson et al. 2004). It is also possible, although not required in the current data, that gravitational radiation torques could enter at high frequencies to help explain the slight excess of sources near $\sim 500 - 600$ Hz.

However, as emphasized by Fred Lamb (private communication), we also need to keep in mind that many of the observed spin frequencies might not represent spin equilibrium. The majority of the sources we observe are accreting at a few percent or less of the Eddington rate, and at this rate it would take hundreds of millions of years to spin up to the observed frequencies. This is comparable to the expected X-ray active lifetimes, so it is possible that many of the observed sources have not yet reached equilibrium. It is therefore important to be cautious in the interpretation of the current distribution, but the combination of the excess of sources at $\sim 500 - 600$ Hz with the lack of very high frequency sources does suggest that, as previously expected, there is a braking torque at work.

3 Kilohertz Quasi-Periodic Oscillations

More than 20 sources display kHz QPOs. These have been observed extensively, primarily with RXTE, with the result that many fine details are known and no simple model can account quantitatively for all the observations. To get an overview and select promising categories of models it is therefore important to establish the main trends, which we consider to be:

- Sources show a pair of strong QPOs, in the range $\sim 500 - 1300$ Hz.
- Both the lower peak frequency ν_1 and the upper peak frequency ν_2 change

by hundreds of Hertz, during and between observations.

- The separation $\Delta\nu \equiv \nu_2 - \nu_1$ changes by tens of Hertz in a given source, but is always close to $\nu_{\rm spin}$ or $\nu_{\rm spin}/2$.

The variation of the frequencies suggests that the frequencies are determined in the accretion flow, because quantities specifically associated with the star (e.g., the spin frequency or the orbital frequency at the innermost stable circular orbit [ISCO]) only change over timescales long compared with observations. Note, however, that the photons themselves can be generated elsewhere (e.g., at the stellar surface during accretion, as in the sonic point model of Miller et al. 1998); it is only the frequencies that must be established in the accretion disk. The link between the spin frequency and the frequency separation also suggests that (1) the generation of at least one of the QPOs is linked to the spin frequency, and (2) the QPOs are associated with each other.

We can therefore start by asking how the spin frequency can be manifest in the disk flow. Fundamentally, this is because something nonaxisymmetric in the system moves around at the spin frequency, and is therefore fixed to the star. One possibility is a magnetic field that is not aligned with the rotation axis. Another possibility is a "hot spot" on the star, so that it is radiation forces that communicate the spin frequency to the flow. If a hot spot is the right answer, we note that it has to remain fixed relative to the star, so the accretion that produces the hot spot must be funneled. The only available funneling mechanism in the system involves the magnetic field. Therefore, we can say that the involvement of the spin frequency in kHz QPOs means that the magnetic field must have dynamically important effects on the accretion flow.

However, it is also true that most kHz QPO sources do not have persistent pulsations in the accretion-powered emission, as would be expected if the magnetic field were strong. The combination of a weak field with the inferred dynamically important effects of the field suggests resonances as a natural possibility, because resonances can magnify weak forces. We therefore explore resonance ideas in the next section.

4 Resonance Ideas

For there to be a resonance requires some fixed or nearly fixed quantity. The kHz QPOs do not have any strictly fixed quantity associated with them, and some (such as the individual frequencies or the ratio between the upper and lower frequencies) vary substantially for a given source. The quantity that is most nearly fixed (although it, too, varies slightly) is the difference frequency $\Delta\nu = \nu_2 - \nu_1$. It is therefore natural to explore whether a resonance exists that would relate the difference frequency to the stellar spin frequency. Other resonance ideas have been proposed that appear promising as explanations of the frequency ratio 3/2 that often appears in black hole QPOs (e.g., Abramowicz et al. 2002 and other papers), but these initial ideas are not directly applicable to neutron star systems because their frequency ratio is not constant (e.g., Belloni et al. 2005). Inclusion of forcing frequencies might allow these ideas to involve $\nu_{\rm spin}$ (e.g., Lee et al. 2004), but here we will concentrate on ideas of the beat frequency variety.

One idea, involving a vertical oscillation resonance, was proposed by Lamb & Miller (2003). Consider an element of gas in the disk, and assume that this gas is essentially orbiting in a circle at frequency $\nu_{\rm orb}$. Suppose that, *as measured in the rest frame of the element*, the element is subjected to a vertical forcing term with frequency $\nu_{\rm force,rest}$. If the forcing frequency as measured in the orbital frame equals the vertical epicyclic frequency $\nu_{\rm vert}$, then a resonance occurs, leading to enhanced vertical motion. If the forcing frequency is $\nu_{\rm force}$ as measured in a global, nonrotating frame, then the frequency observed in the orbiting frame is $\nu_{\rm force,rest} = \nu_{\rm force} - \nu_{\rm orb}$ and the condition for resonance becomes $\nu_{\rm vert} = \nu_{\rm force} - \nu_{\rm orb}$, so $\nu_{\rm vert} + \nu_{\rm orb} = \nu_{\rm force}$.

The vertical epicyclic frequency is very close to the orbital frequency for all radii of interest. Therefore, if the forcing frequency in the global frame is the stellar spin frequency then the resonance condition is roughly $2\nu_{\rm orb} \approx \nu_{\rm spin}$, implying a resonance at $\nu_{\rm orb} \approx \nu_{\rm spin}/2$. As discussed in Lamb & Miller (2003), the combination of enhanced vertical motion at this resonance and clumps near the sonic radius (which changes with accretion rate and source state) can lead to an observed QPO frequency separation $\Delta\nu \approx \nu_{\rm spin}/2$ for very clumpy flow near the resonance, but $\Delta\nu \approx \nu_{\rm spin}$ for smoother flow. This is consistent with observations if smooth flow corresponds to lower spin frequencies and hence larger resonance radii (in practice there is a sharp separation between $\Delta\nu \approx \nu_{\rm spin}/2$ when $\nu_{\rm spin} < 400$ Hz and $\Delta\nu \approx \nu_{\rm spin}$ when $\nu_{\rm spin} > 400$ Hz; see Muno et al. 2001).

5 Current and Future Inferences from Kilohertz QPOs

Because most of the spin of neutron stars in LMXBs is likely to be produced by accretion, it is highly probable that the spin axis of the neutron star is aligned with the axis of the accretion disk. In such coplanar prograde orbits, the highest natural frequency at a given radius is the orbital frequency, but this is also very close to the vertical epicyclic frequency (which is related to the upper QPO frequency in some models, e.g., Stella & Vietri 1998). Most models therefore identify the higher frequency ν_2 with $\sim \nu_{\rm orb}$, regardless of details. As discussed by Miller et al. (1998), this identification, combined with the constraints that (1) the orbit is outside the star and (2) the orbit is outside the ISCO (to allow the high observed quality factor), implies an upper limit on both the radius and the mass of an individual neutron star. For a star with maximum observed qpo frequency $\nu_{\rm max}$ and spin parameter $j \equiv cJ/(GM^2)$, these constraints are (Miller et al. 1998)

$$\begin{aligned} M_{\rm max} &= 2.2\ M_\odot(1000\ {\rm Hz}/\nu_{\rm max})(1+0.75j) \\ R_{\rm max} &= 19.5\ {\rm km}(1000\ {\rm Hz}/\nu_{\rm max})(1+0.2j)\ . \end{aligned} \tag{1}$$

If one could be confident that a particular QPO is generated very near to the ISCO, then one would immediately have a good estimate of the mass of the star. More importantly, one would have evidence for a prediction of general relativity (the existence of unstable orbits) that has no parallel in Newtonian gravity. Such a discovery would therefore have tremendous importance, hence it would need to be subjected to a rigorous critical examination.

What might constitute evidence for the ISCO? We know that the frequencies of the QPOs tend to increase with increasing mass accretion rate. However, we also know that the maximum QPO frequency is roughly the orbital frequency at the ISCO. Therefore, a frequency versus accretion rate behavior that has the usual steep increase followed by a flattening at some frequency, seen reproducibly at a particular frequency for a given source, could be a signature of the ISCO. Similarly, a sharp drop in the amplitude or quality factor at a fixed frequency for a given source might be caused by the ISCO. Tentative evidence for such signatures has been reported for 4U 1820–30 (Zhang et al. 1998) and possibly for 4U 1636–536 (D. Barret et al., in preparation), but the complexities of source behavior make it challenging to identify with confidence any unique effects of the ISCO (see, e.g., the discussion in Méndez et al. 1999). Additional follow-up work will be necessary to evaluate the robustness of these results, but it is encouraging that we are beginning to see possible signs of this important strong gravity effect.

A future high-area X-ray timing mission would make major contributions to this and other studies. The kHz QPOs tend to have lower amplitudes and higher frequencies at higher fluxes, and for some sources the observed flux continues to rise even after the QPO is undetectable. Straightforward extrapolation for some sources suggests that they could reach frequencies as high as ~ 1500 Hz (M. van der Klis, personal communication), which is a range where we expect the effects of the ISCO to be important for most stars. A detector with ten times the area of RXTE would be able to observe such QPOs, and would also allow qualitative advances such as the observation of QPOs during their coherence time (M. van der Klis, personal communication), which is currently impossible.

More generally, we can look back at the work with RXTE and appreciate what it has facilitated. Prior to RXTE there was no suspicion of kilohertz QPOs in neutron stars. Now, they are well-characterized observationally and have been used to produce the most constraining upper limits to the radii of neutron stars. We have reason for optimism that the next generation of observatories will allow us to take the next step, to precise characterization of strong gravity and dense matter.

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