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PULSE AMPLITUDE DEPENDS ON kHz QPO FREQUENCY IN THE ACCRETING MILLISECOND PULSAR SAX J1808.4–3658

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ABSTRACT

We study the relation between the 300–700 Hz upper kHz quasi-periodic oscillation (QPO) and the 401 Hz coherent pulsations across all outbursts of the accreting millisecond X-ray pulsar SAX J1808.4–3658 observed with the *Rossi X-ray Timing Explorer*. We find that the pulse amplitude systematically changes by a factor of ∼2 when the upper kHz QPO frequency passes through 401 Hz: it halves when the QPO moves to above the spin frequency and doubles again on the way back. This establishes for the first time the existence of a direct effect of kHz QPOs on the millisecond pulsations and provides a new clue to the origin of the upper kHz QPO. We discuss several scenarios and conclude that while more complex explanations can not formally be excluded, our result strongly suggests that the QPO is produced by azimuthal motion at the inner edge of the accretion disk, most likely orbital motion. Depending on whether this azimuthal motion is faster or slower than the spin, the plasma then interacts differently with the neutron-star magnetic field. The most straightforward interpretation involves magnetospheric centrifugal inhibition of the accretion flow that sets in when the upper kHz QPO becomes slower than the spin.

Key words: pulsars: general – stars: neutron – X-rays: binaries – X-rays: individual (SAX J1808.4-3658)

1. INTRODUCTION

The low-mass X-ray binary SAX J1808.4–3658 (SAX J1808) is a 401 Hz accreting millisecond X-ray pulsar (AMXP; Wijnands & van der Klis 1998) with a 2 hr orbital period (Chakrabarty & Morgan 1998). The system is an X-ray transient and has shown five X-ray outbursts between 1998 and 2011 (Hartman et al. 2008; Patruno et al. 2012) that were observed with the *Rossi X-ray Timing Explorer* (*RXTE*). The pulsations of SAX J1808 are near-sinusoidal with amplitudes of 2%–7% (Hartman et al. 2008, 2009; Patruno et al. 2012). They are produced by thermal hotspots, emission regions near the stellar magnetic poles, undergoing periodic aspect variations due to the stellar spin (Davidson & Ostriker 1973; Ghosh & Lamb 1978). The hotspots, which may cover a large fraction of the surface (Lamb et al. 2009), are heated by the impact of plasma channeled by the magnetic field toward the poles. The pulsations therefore offer a direct probe of the inner accretion flow and specifically of the magnetic threading of the accretion disk.

SAX J1808 was the first AMXP discovered (Wijnands & van der Klis 1998), and also the first pulsar to show the twin kHz quasi-periodic oscillations (QPOs; Wijnands et al. 2003) now known to be ubiquitous among accreting low-magnetic field neutron stars (van der Klis 2006). In SAX J1808 usually only the higher-frequency of the twin peaks is observed (Wijnands et al. 2003; van Straaten et al. 2005), at frequencies up to 700 Hz, and it is this upper kHz QPO we report on here. The lower kHz QPO is seen only on rare occasions (Wijnands et al. 2003).

Some kHz QPO models explain the upper kHz QPO with orbital motion of short-lived inhomogeneities at some preferred radius in the accretion flow (van der Klis et al. 1996; Strohmayer et al. 1996; Miller et al. 1998; Stella & Vietri 1999; Kluźniak et al. 2004; Alpar & Psaltis 2008), others invoke alternative mechanisms (Lai 1998; Kato 2004; Zhang 2004; Bachetti et al. 2010), but for lack of observational clues the correct interpretation has remained elusive.

Although both the plasma channeling responsible for the X-ray pulsations and the mechanism producing the kHz QPOs are believed to probe the inner accretion flow of AMXPs, no direct relation between pulsations and kHz QPOs has been observed so far. In this Letter we show that such a direct relation does in fact exist in SAX J1808. This provides a new clue to the origin of the upper kHz QPO and the nature of the inner accretion flow toward this AMXP.

2. DATA REDUCTION

We consider all pointed observations of SAX J1808 with *RXTE* using the Proportional Counter Array (Jahoda et al. 2006). Each observation consists of one or multiple continuous 3 ks exposures as set by the data gaps associated with the 95 minute satellite orbit. We use the 16 s time-resolution Standard-2 data to create 2–16 keV light curves, which we normalize to the Crab (see, e.g., van Straaten et al. 2003 for details).

For the stochastic timing analysis we use all GoodXenon and Event data in the 2–20 keV energy range. We compute Leahy normalized (Leahy et al. 1983) power spectra, using 256 s data segments binned to a 1/8192 s (∼122 μs) time resolution, giving a frequency resolution of 1/256 Hz and a Nyquist frequency of 4096 Hz. No background subtraction or dead-time correction was done before a power spectrum was calculated. The resulting power spectra were averaged over intervals of 1–15 ks (depending on the number of active PCUs, which was higher for observations early in the *RXTE* mission) as required to significantly detect the upper kHz QPO.

We subtracted a modeled Poisson noise power spectrum (Zhang et al. 1995) from the averaged power spectra using the method of Klein-Wolt et al. (2004). Accounting for the background emission, we then renormalized the power spectra to source fractional rms squared per Hz (van der Klis 1995). We fitted the power spectra with a set of Lorentzian profiles (Belloni et al. 2002), with each profile $L_i(\nu|\nu_{0,i}, W_i, r_i)$, a function of Fourier frequency ν, described by three parameters: the centroid frequency $\nu_{0,i}$, the FWHM W_i, and the fractional

rms

$$r_i = \sqrt{\int_0^\infty L_i(\nu)d\nu}. \qquad (1)$$

The subscript i refers to the specific power spectral component; in particular, L_u represents the upper kHz QPO.

When its centroid frequency is high, L_u has good coherence and appears as a narrow peak in the power spectrum; as the frequency decreases, so does the coherence and L_u becomes a broad noise component. We only consider the observations for which L_u has good coherence (quality factor $Q \equiv \nu_0/W > 2$).
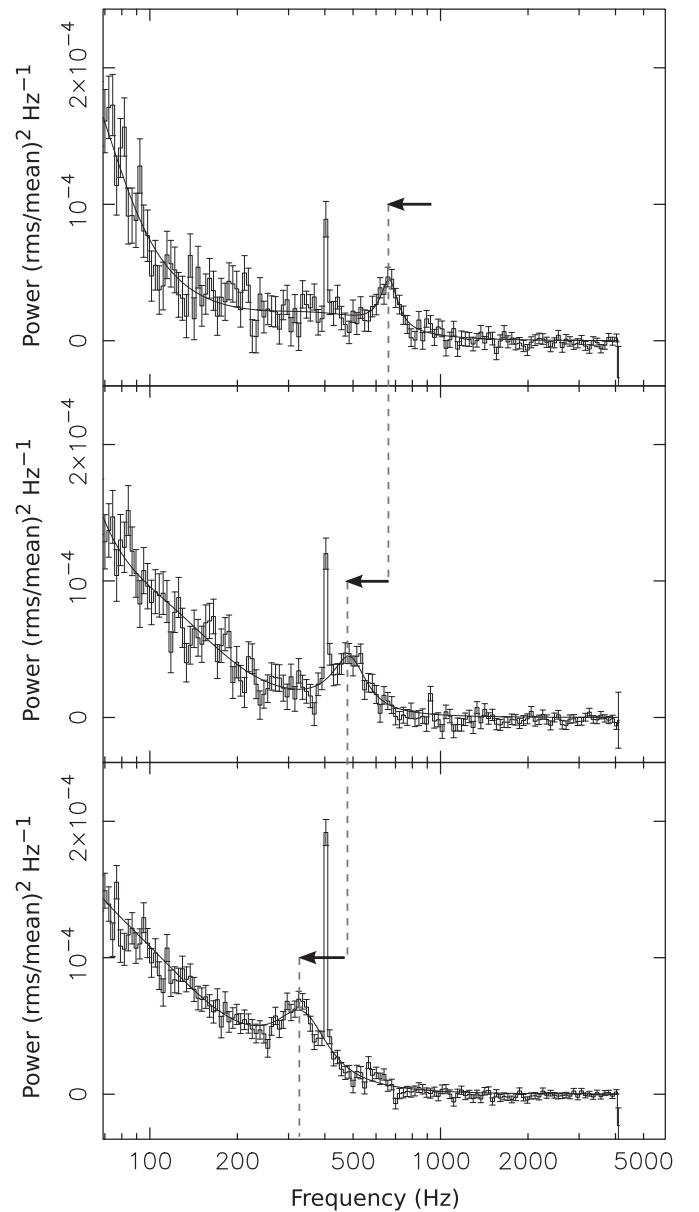
For the analysis of the coherent pulsations we use the same data selection as for the stochastic analysis. We correct the photon arrival times to the solar system barycenter with the FTOOL FAXBARY using the optical source position of Hartman et al. (2008), and subsequently correct the data for the binary orbital ephemeris (Hartman et al. 2008, 2009; Patruno et al. 2012). The power spectra of Figure 1 were made from data corrected in this way, and rebinned such that the pulse fundamental occupies a single frequency bin. In our coherent analysis of the pulsations, we fold the data on the pulse period (Hartman et al. 2008) and for each pulse waveform measure the sinusoidal amplitude[1] of the fundamental and second harmonic, which we express as a fraction of the mean flux.

3. RESULTS

In the course of a typical two week outburst the X-ray flux first rises to ∼70 milliCrab and then falls back down. In correlation to this, the upper kHz QPO drifts from ∼300 Hz up to ∼700 Hz and back down again, and so transits the 401 Hz spin frequency twice per outburst. We find that at these transits the amplitude of the pulsations abruptly changes by a factor ∼2: it halves when in the rise the QPO moves to above the spin frequency and then, as illustrated in Figure 1, doubles again on the way back.

We observed three such transitions at high signal-to-noise: two where the pulse amplitude approximately halves during the outburst rises in 2005 and 2008, and one where it approximately doubles during the decay in 2002. Figure 2 shows the QPO frequency (top frames) and the pulse amplitude (bottom frames) across these three transitions. In each case the pulse amplitude can be seen to systematically drop when the QPO moves to frequencies >401 Hz (blue points), and to be systematically higher when the QPO is at or below the spin frequency (red points). In 2002, the observations sample the source during the actual transition (gray bands). The pulse amplitude increases steadily from 3.5% to 5.6% on a timescale of hours when simultaneously the QPO frequency drifts down from ∼520 to ∼400 Hz. Both amplitude and frequency change very significantly (17σ and 8σ, respectively; see Table 1). In 2005 and 2008 we observe the opposite transition, with behavior that is entirely consistent with that in 2002, but time-reversed. The pulse amplitude drops from 7.1% to 4.3% (28σ) and 6.5% to 3.3% (23σ) in 2005 and 2008, respectively, when the QPO frequency increases through the 400–520 Hz range (12σ and 5σ change). In all cases, for QPO frequencies <401 Hz the pulse amplitude remains at the high level attained near 401 Hz.

The pulsations of SAX J1808 have been studied extensively (Hartman et al. 2008; Leahy et al. 2008; Hartman et al. 2009; Ibragimov & Poutanen 2009; Kajava et al. 2011; Morsink &

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[1] Note that we report *sinusoidal* amplitudes, which are a factor of $\sqrt{2}$ larger than *rms* amplitudes.
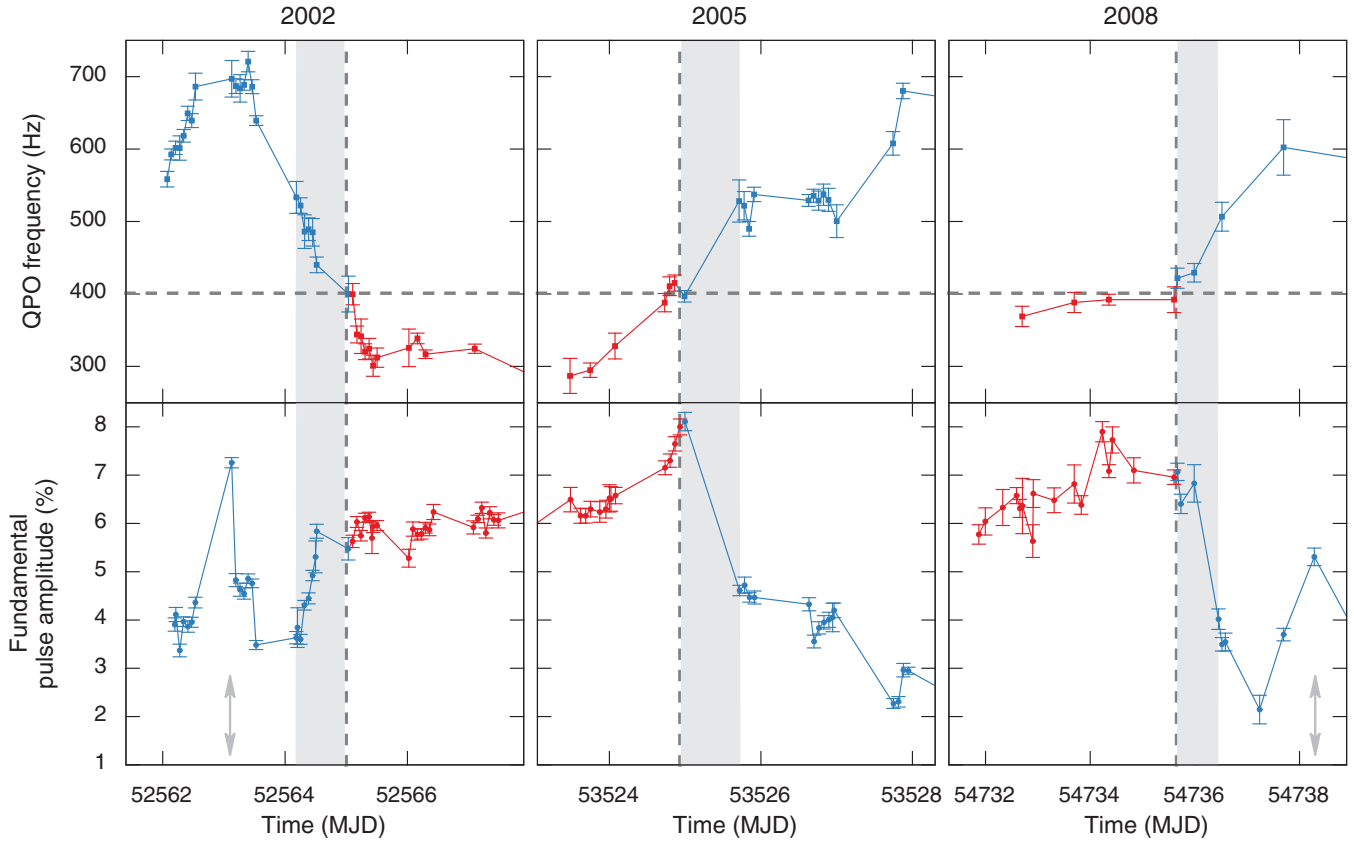

Figure 1. Power spectral evolution during the 2002 outburst, in chronological order (top-down). The frequency evolution of the kilohertz QPO (broad peak) in relation to the spike caused by the strictly periodic 401 Hz pulsations is obvious. When the kHz QPO frequency (dashed lines) moves through the spin frequency (second to third frame) the pulse amplitude (height of the spike) increases drastically. Arrows indicate the changes in QPO frequency and the initial spike height.

Leahy 2011; Patruno et al. 2012) and are known to show brief, hour-timescale excursions in amplitude. We define an excursion as a sudden pulse amplitude increase of 50% or more directly followed by a similar amplitude decrease, such that the entire episode verifiably takes place within two days. In total there are 11 such excursions in the data, and we have marked these in Figures 2 and 3 with double-headed gray arrows.

We find that the occurrence of these brief excursions depends on QPO frequency dichotomously. The excursions only occur when the QPOs are >401 Hz (see, e.g., Figure 3). While they are not limited to any particular QPO frequency, the most pronounced excursions cluster around the highest QPO frequencies of 600–700 Hz.

Figure 2. Evolution of the upper kHz QPO frequency (top frame) and the sinusoidal pulse amplitude (bottom frame) as the QPO frequency passes through the 401 Hz spin frequency during outbursts in the years indicated. Observations with the QPO frequency above and below the spin frequency are marked in blue and red, respectively. The dashed lines mark the spin-frequency passages and the gray bands indicate the full extent of the transits between the two regimes. The double-headed arrows mark pulse amplitude excursions (see the text).

Table 1
Spin-frequency Transit Measurements

Outburst	Date (MJD)	Exposure (s)	QPO Frequency (Hz)	A_1 (%)	A_2 (%)
2002	52564.18	2800	538 ± 16	3.49 ± 0.09	0.76 ± 0.09
	52564.97	3900	392 ± 10	5.63 ± 0.05	0.63 ± 0.05
2005	53524.96	17500	397 ± 7	7.10 ± 0.07	1.19 ± 0.07
	53525.72	13900	518 ± 7	4.35 ± 0.07	1.35 ± 0.07
2008	54735.69	10700	416 ± 10	6.49 ± 0.09	0.98 ± 0.09
	54736.44	12700	512 ± 18	3.33 ± 0.10	1.34 ± 0.10

Notes. Listing (left to right): the time of observation, total exposure, upper kHz QPO frequency and the fundamental (A_1) and second harmonic (A_2) sinusoidal pulse amplitudes just before and after each transition for the indicated outbursts. The significances of these changes were calculated from the errors on the differences using standard error propagation.

Figure 4 shows the amplitudes of the pulse fundamental (top frame) and second harmonic (bottom frame) versus upper kHz QPO centroid frequency as we measured them in all data across all outbursts. The large step in pulse amplitude taking place over a QPO frequency range of 400–500 Hz is obvious. When in this transition the fundamental amplitude drops from ∼6% to ∼3%, the weaker second harmonic instead strengthens from ∼0.9% to ∼1.6%. The clustering of the brief excursions at high QPO frequencies is also clear among the points >650 Hz.

The remaining data, at lower signal-to-noise, show behavior consistent with that in the three transitions reported above. When in 2005 at MJD 53536.1 The QPO moves from above to below 401 Hz, the pulse amplitude increases. In 1998 there

is no transition; the QPO peak, while broad, is always entirely below 401 Hz. Consistent with this, the pulsations are strong and the second harmonic is weak. In 2011 kHz QPOs are detected only at frequencies >401 Hz, so no transition is observed. In this outburst the pulse amplitude is ∼4% with, as expected, amplitude excursions of 2%–3% on top of this.

4. DISCUSSION

Our analysis establishes, for the first time, a direct effect of kHz QPOs on the millisecond pulsations: a large change in pulsation properties occurs when the upper kHz QPO frequency transits through the spin frequency, but reversely a change in
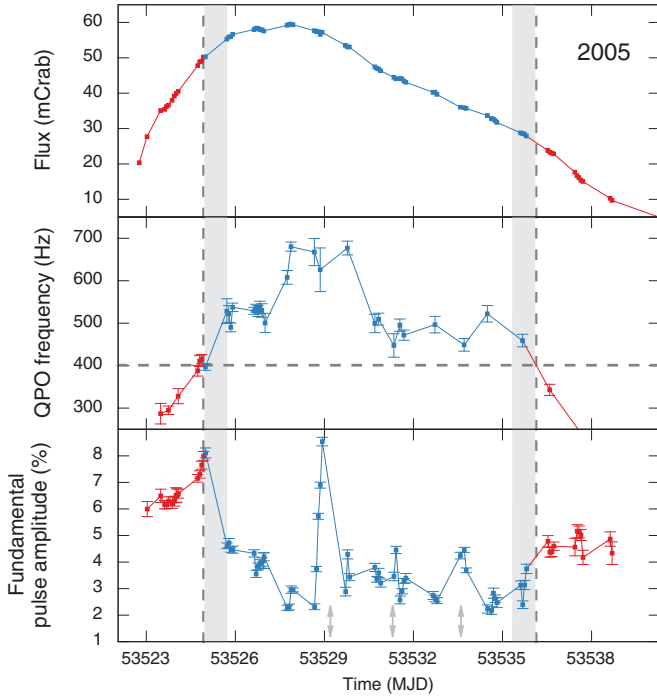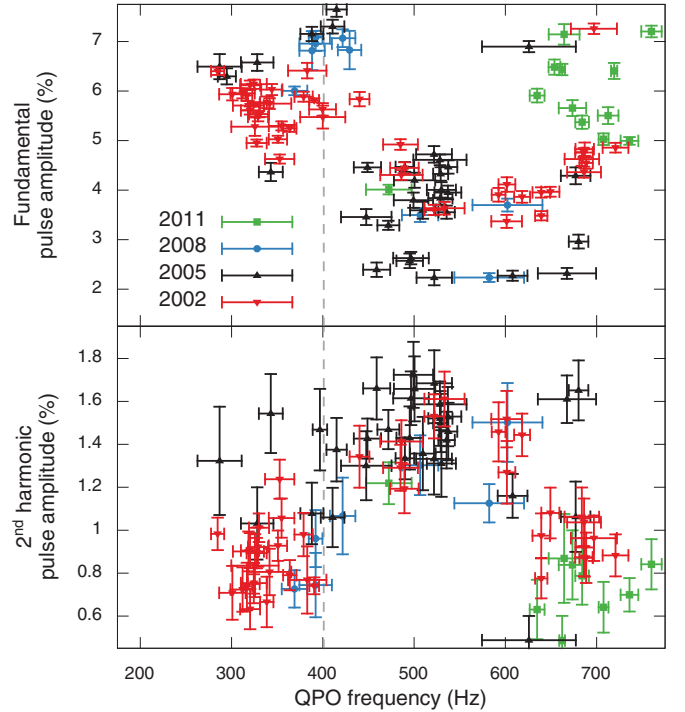
Figure 3. Overview of the 2005 outburst, showing the X-ray flux (top frame), the upper kHz QPO frequency (middle frame), and the fundamental pulse amplitude (bottom frame) as a function of time. Observations with the QPO frequency above and below the spin frequency are marked in blue and red, respectively. The dashed lines mark the spin-frequency passages and the gray bands show the extents of the transits between the two regimes. The double-headed arrows mark pulse amplitude excursions (see the text). The other outbursts show similar trends.

Figure 4. Fundamental (top frame) and second harmonic (bottom frame) pulse amplitudes as a function of the upper kHz QPO frequency of the outbursts as indicated. The dashed line marks the spin frequency.

pulse amplitude does not predict the QPO frequency. These findings point toward an origin of the upper kHz QPO in a process involving azimuthal motion in the accretion flow that makes the accreting plasma interact differently with the neutron-star magnetic field depending on whether the azimuthal motion is faster or slower than the spin. Although spin resonances may play a role (see below), mechanisms relying on a resonance of the QPO frequency itself with the spin cannot explain our observations: the amplitude of such a resonance is largest when the QPO frequency is near 401 Hz and diminishes away from the resonant frequency. Instead, what is required is a step-wise change in the pulsations between QPO frequencies above and below the spin frequency.

Our observation that the pulse amplitude is sensitive to whether the QPO frequency is faster or slower than the spin immediately suggests an interpretation where the QPO is due to orbital motion and the key physics involved is the centrifugal force experienced by the accreting plasma as it enters the magnetosphere (Illarionov & Sunyaev 1975; Ghosh & Lamb 1978). In such a scenario, plasma outside the magnetosphere orbits in a Keplerian disk. Inside the magnetosphere the motions are dominated by the magnetic field and so the plasma is forced to corotate with the stellar spin. As long as the radius of the magnetosphere, r_m, is larger than the corotation[2] radius r_c, the plasma entering the magnetosphere speeds up and hence experiences a centrifugal force exceeding gravity, inhibiting lateral accretion. For a smaller magnetosphere no such centrifugal inhibition of

the lateral accretion flow will occur and therefore a smaller fraction of the accreting plasma is available to flow out of the disk plane and toward the poles, causing the pulse amplitude to drop. Thus, if the QPO is due to orbital motion at the edge of the magnetosphere and hence the QPO frequency can be identified with the Keplerian frequency at r_m, a very different accretion pattern is predicted for QPO frequencies above and below the spin frequency.

Another possible mechanism that can explain our result can apply to any model in which the QPO is due to an azimuthal motion at the inner edge of the disk. This motion could be Keplerian, but might also be, e.g., precessional, or that of an azimuthally propagating disk wave (van der Klis 2006, and references therein). As the inner edge of the disk moves inward it will pass through a resonance radius, r_r, where the QPO frequency equals the spin frequency and a resonance may occur. For even smaller inner disk radii the QPO frequency increases further, but the resonance may continue to exist in the disk at r_r. It is at least logically possible that such a resonance present in the disk flow at radius r_r leads to a different accretion pattern at radii inside r_r. How precisely the resonance affects the pulse amplitude remains unspecified in this scenario, which in this generic sense could formally even work for an azimuthally symmetric QPO mechanism, and/or by interaction with the pulsar beam instead of the magnetic field.

In the above two scenarios, the accretion pattern changes when the inner edge of the disk passes through r_c or r_r, respectively. A third possibility is that the relevant radius is r_m. It has been suggested that it is possible for the Keplerian disk to penetrate the magnetosphere and continue its orbital motion inside r_m, with the inner edge of the disk at r_{in} set by radiative stresses (Miller et al. 1998), so that r_{in} can be either larger or smaller than r_m. If the QPO originates from the inner edge of the disk, and its frequency is near the spin frequency as r_{in} passes

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[2] The corotation radius r_c is the radius where the Keplerian frequency equals the spin frequency: $r_c \equiv [\sqrt{GM}/(2\pi\nu_s)]^{2/3} = 31$ km for an $M = 1.4\,M_\odot$, $\nu_s = 401$ Hz star, where M is the neutron-star mass and ν_s its spin frequency.

through r_m, differences in magnetic coupling associated with r_{in} being larger or smaller than r_m might conceivably explain the change in the pulsations. For a QPO caused by Keplerian orbital motion these conditions might be fulfilled, as during outburst SAX J1808 may be near spin-equilibrium ($r_m \simeq r_c$, Hartman et al. 2008).

So, although some more complex explanations cannot formally be excluded, the interpretations discussed here predominantly point to a QPO that is produced by azimuthal motion at the inner edge of the accretion disk, most likely orbital motion, and a change in the interaction of the accreting plasma with the neutron star magnetic field near a QPO frequency equal to the spin frequency. The most straightforward scenario involves centrifugal inhibition of the accretion flow that sets in when the upper kHz QPO becomes slower than the spin. This scenario implies that the QPO is produced by orbital motion at the edge of the magnetosphere as it passes through 401 Hz.

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