Quasi-periodic X-ray brightness fluctuations in an accreting millisecond pulsar

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ABSTRACT

The relativistic plasma flows onto neutron stars that are accreting material from stellar companions can be used to probe strong-field gravity as well as the physical conditions in the supranuclear-density interiors of neutron stars. Plasma inhomogeneities orbiting a few kilometres above the stars are observable as X-ray brightness fluctuations on the millisecond dynamical timescale of the flows⁴⁻³. Two frequencies in the kilohertz range dominate these fluctuations: the twin kilohertz quasi-periodic oscillations (kHz QPOs). Competing models for the origins of these oscillations (based on orbital motions) all predict that they should be related to the stellar spin frequency⁴⁻¹⁰, but tests have been difficult because the spins were not unambiguously known. Here we report the detection of kHz QPOs from a pulsar whose spin frequency is known. Our measurements establish a clear link between kHz QPOs and stellar spin, but one not predicted by any current model. A new approach to understanding kHz QPOs is now required. We suggest that a resonance between the spin and general relativistic orbital and epicyclic frequencies could provide the observed relation between QPOs and spin.

Twin kHz QPOs with frequencies between 300 and 1,300 Hz occur in more than 20 accreting neutron stars³. In seven of these, during thermonuclear X-ray bursts caused by the explosion of material accumulated on the neutron-star surface, short-lived oscillations are observed with frequencies νburst in the range 270–620 Hz, approximately constant but different in each source, that are thought to be caused by the neutron-star spin¹¹.

The frequency difference ∆ν between the two kHz QPOs is close to either νburst, or νburst/2, depending on the source. This observed commensurability has given rise to beat-frequency models⁶,¹²⁻¹⁴. Such models identify the higher-frequency (“upper”) kHz QPO with the frequency of orbital motion, closely around the neutron star, of the plasma at the inner edge of the accretion disk (within this radius no stable orbits exist and the matter plunges in), and the other (“lower”) kHz QPO with a rotational beat interaction between the upper kHz QPO and the neutron-star spin. These models predict ∆ν to be equal to the spin frequency νspin. In this interpretation, we have either νburst = νspin or νburst = 2νspin, depending on whether one or two hotspots form on the star’s surface during the bursts. Testing this requires searching for harmonic structure in the burst oscillations, but searches¹⁵ are limited in terms of statistics as compared to the case of a true pulsar.

A problem for beat-frequency models is the
fact that $\Delta \nu$ is neither constant\textsuperscript{16,17}, nor exactly equal\textsuperscript{18,19} to $\nu_{\text{spin}}$ (but possible solutions in the beat-frequency models do exist\textsuperscript{20}). This has motivated the proposal of several alternative models to explain the kHz QPOs\textsuperscript{7–10}, all of which, like beat-frequency models, use orbital motion as one of the observed frequencies, but which use another mechanism – such as general relativistic epicyclic motion, which is very fast in these extreme gravitational fields – to generate the other frequency. None of these models predict commensurability between spin and kHz QPO frequencies such as beat-frequency models do. It has been clear for some time that independent measurements of the neutron-star spin frequency could provide the definitive test of the beat-frequency idea. The discovery\textsuperscript{21} of the first accreting millisecond pulsar in 1998 raised the prospect of such a test, but until now no accreting millisecond pulsar has shown the anticipated kHz QPOs.

On 13 October 2002, a bright new outburst of the recurrent X-ray transient and accreting millisecond pulsar, SAX J1808.4–3658, started\textsuperscript{22}. Using the Rossi X-ray Timing Explorer satellite, we obtained ~700 ks of data covering the outburst with daily observations from 15 October to 26 November 2002. We performed a series of fast Fourier transforms to search for kHz QPOs, and discovered several. One kHz QPO was monitored for 12 days (Fig. 1). Its frequency increased from 570 to 725 Hz between 15 and 16 October, then gradually decreased to a minimum of 280 Hz on 21 October, suddenly increased again to 400 Hz the next day, and then resumed its decrease, to 320 Hz on 26 October. After this the QPO was not detected, presumably owing to the limited statistics resulting from the drop in count rate (by a factor of about 4) by this stage of the outburst. On 16 October, a second kHz QPO was detected simultaneously at a frequency of $\Delta \nu = 195 \pm 6$ Hz below the first one (Fig. 1, top panel). In the remaining data, this second QPO was not detected with a significance greater than 2.5$\sigma$. Additional broad noise structures of marginal significance are sometimes present around 350, 220 and 120 Hz.

The frequencies, strengths and coherences of these two kHz QPOs in SAX J1808.4–3658, as well as the variations in their parameters as a function of source luminosity, are very similar to those of the twin kHz QPOs observed in those neutron-star low mass binaries for which no pulsations are seen in their persistent emission (the non-pulsing sources\textsuperscript{3}), so we interpret this as the same phenomenon. The $\sim$195-Hz frequency difference between the two QPOs is the lowest known (in other systems $\Delta \nu$ ranges between 225 and 350 Hz)\textsuperscript{3}. It is far below the 401-Hz spin frequency predicted in simple beat-frequency models\textsuperscript{6,12}, yet there is a clear commensurability: $\Delta \nu$ is consistent with $\nu_{\text{spin}}/2$. This is reminiscent of those non-pulsing sources where $\Delta \nu$ is near $\nu_{\text{burst}}/2$. Hence our results support the spin interpretation of the burst oscillations in those sources, as well as the suspicion that $\nu_{\text{burst}}$ is always near $\nu_{\text{spin}}$ (and never twice that). Moreover, as reported in a companion paper\textsuperscript{23}, in our observations we also detected four thermonuclear bursts in which we discovered burst oscillations at the neutron-star spin frequency. This discovery further strengthens the idea that the burst oscillations are always at the stellar spin frequency.

We now demonstrate that, unless we are wrong about the spin frequency of this pulsar, which seems highly unlikely, our observations falsify current beat-frequency models, yet so pose a severe challenge to all other current kHz QPO models. In beat-frequency models\textsuperscript{6,6,24}, the spin-orbit beat interaction occurs at a frequency $\nu_{\text{beat}} = n(\nu_{\text{orbit}} - \nu_{\text{spin}})$, where $\nu_{\text{orbit}}$ is the orbital frequency, and the positive integer $n$ is a symmetry factor accounting for multiple symmetrically located spin-orbit interaction sites (for example, $n = 2$ for two magnetic poles). Simple beat-frequency models have $n = 1$ and the two kHz QPOs at $\nu_{\text{beat}}$ and $\nu_{\text{orbit}}$, so that $\Delta \nu = \nu_{\text{orbit}} - \nu_{\text{beat}} = \nu_{\text{spin}}$. As noted, this is clearly inconsistent with our observations. In general, $n$ is the least common multiple (LCM) of the number of stellar and the number of orbital interaction sites: $n = \text{LCM}(n_{\text{spin}}, n_{\text{orbit}})$. Whatever the value of these numbers, and even allowing the observed orbital QPO to be at either $\nu_{\text{orbit}}$ or $n_{\text{orbit}}\nu_{\text{orbit}}$, there is no configuration predicting the observed $\Delta \nu = \nu_{\text{spin}}/2$.

The only solution consistent with current beat-frequency models is that $\nu_{\text{spin}}$ is half the observed 401-Hz pulsar frequency (that is, two hotspots) and $n = 1$ (that is, only one pulsar beam or magnetic pole interacts with the orbit). However, the very stringent amplitude upper limit...
of 0.014% root mean square (r.m.s.; E.H.M. et al., manuscript in preparation) on any coherent signal at 200.5 Hz (only 0.38% of the signal at 401 Hz) makes this solution very unlikely: a fine-tuned special geometry would be required to hide the true spin frequency that well. We note that the sonic point beat-frequency model\(^6\) predicts a spectrum of many additional weaker QPO peaks (higher-order sidebands), one of which (for example, abs(\(\nu_{\text{upper}} - 3\nu_{\text{spin}}\)) or, a particularly close match, abs(\(3\nu_{\text{lower}} - 2\nu_{\text{spin}}\)), where \(\nu_{\text{upper}}\) and \(\nu_{\text{lower}}\) are the upper and lower kHz QPO frequency, respectively) could be picked out and identified with a QPO that we observe. However, this would not explain why, contrary to predictions, this peak is stronger rather than much weaker than the main peaks. In our view, the coincidence between \(\Delta \nu\) and \(v_{\text{burst}}/2\) in several other sources strongly suggests instead that the relation between kHz QPOs and neutron star spin is one where (in SAX J1808.4–3658 and in those several other sources) the peaks are separated by \(\nu_{\text{spin}}/2\).

This has not been predicted by any model.

Inspired by the relativistic resonance models of ref. 9 (see also refs 25–27 for related suggestions), we note that there are particular radii in the disk where the difference between the general relativistic orbital frequency (\(\nu_o\)) and radial frequency (\(\nu_r\); note that \(\nu_o - \nu_r\) is the periastron precession frequency) is equal to \(\nu_{\text{spin}}\) and \(\nu_{\text{spin}}/2\). For a 1.4-solar-mass Schwarzschild geometry, these radii are \(\sim\)18 and \(\sim\)23 km, respectively (the best match to the observed frequencies in fact occurs at 1.1 solar masses, but see below). If a radiatively or magnetically mediated spin-orbit interaction were to set up a resonance at one of those radii leading to kHz QPOs at \(\nu_o\) and \(\nu_r\), this could explain the observed frequency commensurabilities with no involvement of a beat frequency. Whether \(\Delta \nu\) is \(\nu_{\text{spin}}\) or \(\nu_{\text{spin}}/2\) might depend on whether or not the relevant radius is within the inner edge of the disk; in support of this, we note that all four systems where \(\Delta \nu \approx \nu_{\text{spin}}/2\) are those where \(\nu_{\text{spin}}\) exceeds 400 Hz, and vice versa for the remaining three cases. That the frequencies can shift and the observed commensurabilities are often not exact might be related to a mechanism similar to that which makes the resonances occur off the naively expected integer ratios in the numerical calculations of ref. 28. We note that this combination of ideas (adding the spin as an ingredient in the relativistic resonance model) can lead to a single framework within which the apparently discrepant frequency commensurabilities observed in black holes (which take the form of integer ratios) as well as neutron stars can both be understood in terms of resonances at privileged radii in an accretion disk, namely those radii where the general relativistic epicyclic frequencies (and, in the case of the neutron-star systems, spin) are commensurate.

A surprising third QPO (Fig. 2) near 410 Hz was detected on four occasions, just above the 401-Hz pulse frequency. Its frequency increased from 409.3±0.7 to 413.5±0.2 Hz while the frequency of the upper kHz QPO increased from 328±4 to 390±5 Hz. This third kHz QPO is a phenomenon not previously seen, and is probably related to the pulsating nature of SAX J1808.4–3658. To some extent, it resembles the sideband to the lower kHz QPO observed\(^{29}\) in three non-pulsing kHz QPO sources: the 410-Hz QPO might be a sideband to the pulsation with a similar underlying mechanism. These lower kHz QPO sidebands were suggested\(^{29}\) to be due to Lense-Thirring precession, a predicted – but not yet observed – general relativistic wobble of the orbital plane (nodal precession). The precession frequency is predicted\(^{30}\) to be quadratically related to the orbital frequency itself, and in the case of both the QPO sidebands and the ~410-Hz QPO this is consistent with observations. However, as Lense-Thirring precession is prograde, a beat between a pulsar beam and a precessing orbit would produce a sideband below, rather than the observed sideband above, the pulsar frequency. Another resonance, perhaps at the radius where the general relativistic vertical epicyclic frequency matches \(\nu_{\text{spin}}\), might be considered as an explanation of this phenomenon.

REFERENCES

1. Svartsman, V. F. Halos around black holes. Sov. Astron. 15, 377–384 (1971).
2. Van der Klis, M. et al. Intensity dependent quasi-periodic oscillations in the X-ray flux of GX 5-1. Nature 316, 225–230 (1985).
3. Van der Klis, M. Millisecond oscillations in X-ray binaries. Annu. Rev. Astron. Astrophys. 38, 717–760 (2000).
4. Alpar, M. A. & Shaham, J. Is GX 5-1 a millisecond pulsar? *Nature* 316, 239–241 (1985).

5. Lamb, F. K., Shibazaki, N., Alpar, M. A. & Shaham, J. Quasi-periodic oscillations in bright galactic bulge X-ray sources. *Nature* 317, 681–687 (1985).

6. Miller, C. M., Lamb, F. K. & Psaltis, D. Sonic-point model of kilohertz quasi-periodic brightness oscillations in low-mass X-ray binaries. *Astrophys. J.* 508, 791–830 (1998).

7. Stella, L. & Vietri, M. KHz quasi-periodic oscillations in low-mass X-ray binaries as probes of general relativity in the strong-field regime. *Phys. Rev. Lett.* 82, 17–20 (1999).

8. Titarchuk, L., Lapidus, I. & Muslimov, A. Mechanisms for high-frequency quasi-periodic oscillations in neutron stars and black hole binaries. *Astrophys. J.* 449, 315–328 (1998).

9. Kluźniak, W. & Abramowicz, M. A. The physics of kHz QPOs strong gravity coupled anharmonic oscillators. *Astrophys. J. Lett.* (submitted); preprint at http://xxx.lanl.gov/astro-ph/0105057 (2001).

10. Psaltis, D. & Norman, C. On the origin of quasi-periodic oscillations and broad-band noise in accreting neutron stars and black holes. *Astrophys. J.* (submitted); preprint at http://xxx.lanl.gov/ astro-ph/0001391 (2000).

11. Strohmayer, T. & Bildsten, L. New views of thermonuclear bursts. In *Compact Stellar X-ray Sources* (eds Lewin, W. H. G. & van der Klis, M.) (Cambridge Univ. Press, in the press); preprint at http://xxx.lanl.gov/astro-ph/0301544 (2003).

12. Strohmayer, T. E. *et al.* Millisecond X-ray variability from an accreting neutron star system. *Astrophys. J.* 469, L9–L12 (1996).

13. Cui, W. On the disappearance of kilohertz quasi-periodic oscillations at high mass accretion rate in low-mass X-ray binaries. *Astrophys. J.* 534, L31–L34 (2000).

14. Campana, S. Kilohertz quasi-periodic oscillations in low-mass X-ray binary sources and their relation to the neutron star magnetic field. *Astrophys. J.* 534, L79–L82 (2000).

15. Muno, M. P., Özel, F. & Chakrabarty, D. The amplitude evolution and harmonic content of millisecond oscillations in thermonuclear X-ray bursts. *Astrophys. J.* 581, 550–561 (2002).

16. Van der Klis, M., Wijnands, R. A. D., Horne, K. & Chen, W. Kilohertz quasi-periodic oscillation peak separation is not constant in Scorpius X-1. *Astrophys. J.* 481, L97–L101 (1997).

17. Méndez, M. *et al.* Kilohertz quasi-periodic oscillation peak separation is not constant in the atoll source 4U 1608-52. *Astrophys. J.* 505, L23–L26 (1998).

18. Méndez, M., van der Klis, M. & van Paradijs, J. Difference frequency of kilohertz QPOs not equal to half the burst oscillation frequency in 4U 1636-53. *Astrophys. J.* 506, L117–L119 (1998).

19. Jonker, P. G., Méndez, M. & van der Klis, M. Kilohertz quasi-periodic oscillations difference frequency exceeds inferred spin frequency in 4U 1636-53. *Mon. Not. R. Astron. Soc.* 336, L1–L5 (2002).

20. Lamb, F. K. & Miller, M. C. Changing frequency separation of kilohertz quasi-periodic oscillations in the sonic-point beat-frequency model. *Astrophys. J.* 554, 1210–1215 (2001).

21. Wijnands, R. & van der Klis, M. A millisecond pulsar in an X-ray binary system. *Nature* 394, 344–346 (1998).

22. Markwardt, C. B., Miller, J. M. & Wijnands, R. SAX J1808.4–3658. *IAU Circ.* No. 7993 (2002).

23. Chakrabarty, D. *et al.* Nuclear-powered millisecond pulsars and the maximum spin frequency of neutron stars. *Nature* (this issue).

24. Shibazaki, N. & Lamb, F. K. Power spectra of quasi-periodic oscillations in luminous X-ray stars. *Astrophys. J.* 318, 767–785 (1987).

25. Psaltis, D. Models of quasi-periodic variability in neutron stars and black holes. *Adv. Space Res.* 355, 786–800 (2001).

26. Stella, L. in *X-ray Astronomy: Stellar Endpoints, AGN, and the Diffuse X-ray Background* (eds White, N. E., Malaguti, G. &
Palumbo, G. G. C.) 365–375 (AIP Conference Proceedings Vol. 599, Melville, New York, 2001).

27. van der Klis, M. in XEUS—Studying the Evolution of the Hot Universe (eds Hasinger, G., Boller, Th. & Parmar, A.) 354–362 (MPE Report 281, 2002).

28. Abramowicz, M. A., Karas, V., Kluźniak, W., Lee, W. H. & Rebusco, P. Non-linear resonance in nearly geodesic motion in low-mass X-ray binaries. *Publ. Astron. Soc. Jpn* 55, 467–471 (2003).

29. Jonker, P. G., Méndez, M. & van der Klis, M. Discovery of a new, third kilohertz quasi-periodic oscillations in 4U 1608-52, 4U 1728-34, and 4U 1636-53: Sidebands to the lower kilohertz quasi-periodic oscillation? *Astrophys. J.* 540, L29–L32 (2000).

30. Stella, L. & Vietri, M. Lense-Thirring precession and quasi-periodic oscillations in low-mass X-ray binaries. *Astrophys. J.* 492, L59–L62 (1998).

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This 2-column preprint was prepared with the AAS LaTeX macros v5.0.
The power-density spectrum obtained for SAX J1808.4–3658 using the combined data from 18–19 October and 22–26 October. The power is given in units of \((\text{r.m.s./mean})^2/(\text{Hz} \times 10^{-3})\). This spectrum is for the photon energy range 3–60 keV, and shows the presence of the pulsations at 401 Hz, the upper kHz QPO, the \(\sim 410\)-Hz QPO, and broadband noise below a few hundred hertz. The spectrum was fitted with the same function as described in Fig. 1, but with an extra lorentzian function to fit the extra QPO at \(\sim 410\) Hz. The extra QPO could be detected significantly on four occasions: in the combined 18–19 October data, the 22 October data, the combined 23–24 October data, and the combined 25–26 October data. Combining all those data, the QPO was significant at a 6.5\(\sigma\) level. This QPO had an r.m.s amplitude of \(\sim 2.5\%\) (for the energy range 3–60 keV) and its width (FWHM) was between 2 and 8 Hz.