Nuclear-powered millisecond pulsars and the maximum spin frequency of neutron stars

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Millisecond pulsars are neutron stars that are thought to have been spun-up by mass accretion from a stellar companion.1 It is unknown whether there is a natural brake for this process, or if it continues until the centrifugal breakup limit is reached at submillisecond periods. Many neutron stars that are accreting mass from a companion star exhibit thermonuclear X-ray bursts that last tens of seconds, caused by unstable nuclear burning on their surfaces.2 Millisecond-period brightness oscillations during bursts from ten neutron stars (as distinct from other rapid X-ray variability that is also observed3,4) are thought to measure the stellar spin,2,5 but direct proof of a rotational origin has been lacking. Here, we report the detection of burst oscillations at the known spin frequency of an accreting millisecond pulsar, and we show that these oscillations always have the same rotational phase. This firmly establishes burst oscillations as nuclear-powered pulsations tracing the spin of accreting neutron stars, corroborating earlier evidence.5,6 The distribution of spin frequencies of the 11 nuclear-powered pulsars cuts off well below the breakup frequency for most neutron star models, supporting theoretical predictions that gravitational radiation losses can limit accretion torques in spinning up millisecond pulsars.7–9

The millisecond oscillations observed during X-ray bursts are not perfectly coherent, but usually drift in frequency by several hertz over the course of a burst, generally reaching an asymptotic maximum frequency that is repeatable in a given neutron star.2 This frequency drift has been interpreted as arising from angular momentum conservation in a decoupled surface burning layer that expands and contracts during the burst, so that the asymptotic frequency is the stellar spin frequency.10,11 A puzzle in this picture is why the oscillation persists late in the burst, well after the nuclear burning has spread over the entire star. Also, in most of these neutron stars, unexplained pairs of kilohertz quasi-periodic oscillations (kHz QPOs) are also observed in the non-burst X-ray emission, with the QPO separation frequency approximately equal to either the burst oscillation frequency or half this value,3 posing a further puzzle (see ref. 4 for new insight into this problem).

We have observed the transient X-ray source SAX J1808.4–3658, which has been detected in four outbursts since its discovery (September 1996, April 1998, January 2000, and October 2002), each lasting several weeks. It was previously established that the source is a weakly magnetized (< 10^{10} G), rapidly rotating (401 Hz) accreting neutron star in a 2 hr low-mass X-ray binary.12–14 We observed it during its 2002 X-ray outburst for about 700,000 seconds between 15 October and 26 November using the Proportional Counter Array (PCA) on the Rossi X-Ray Timing Explorer (RXTE). As in the two previous outbursts observed by RXTE, persistent 401 Hz accretion-powered X-ray pulsations13 modulated by the 2 hr binary orbit14 were detected throughout our observations, with a fractional r.m.s. amplitude of 3–5%. The pulsar spin frequency derived from these data was approximately 400.97521 Hz at the start of the outburst, with a mean spin-down rate of about 2 × 10^{-13} Hz s^{-1}; a detailed discussion of the pulsar’s spin evolution will be presented elsewhere. Four thermonuclear X-ray bursts were also detected on 15, 17, 18, and 19 October; these are among the brightest X-ray bursts ever observed by RXTE from any neutron star. Previous analysis of observations from the 1996 outburst of SAX J1808.4–3658 with the BeppoSAX satellite yielded a marginal detection of a 400±2 Hz oscillation during a bright X-ray burst.15

Strong millisecond oscillations around 401 Hz were clearly detected in all four X-ray bursts in the October
amplitudes are comparable to those of the persistent (non-burst) accretion-powered pulsations even though the burst emission is considerably brighter than the persistent emission, indicating that the burst flux itself must be pulsed. The burst oscillations are sinusoidal in shape, with a 2σ upper limit of <0.5% on the fractional r.m.s. amplitude of an 802 Hz harmonic, compared to a measured mean harmonic amplitude of 0.4% for the persistent pulsations.

The observed frequency drift demonstrates that this is a similar phenomenon as the burst oscillations observed in ten other neutron stars, although the oscillations in this neutron star have some unusual traits. The frequency drift is among the largest observed in any neutron star\textsuperscript{17,18} (Δν ≈5 Hz, Δν/ν ≈1%). Also, the drift time scale is an order of magnitude faster than in the other neutron stars,\textsuperscript{16} and the maximum oscillation frequency is reached during the burst rise, inconsistent with angular momentum conservation in a cooling, contracting shell. In fact, the oscillation overshoots the spin frequency during the burst rise. The rapid frequency drift may be an indication that SAX J1808.4–3658 has a stronger magnetic field than the other neutron stars, since a sufficiently strong field will suppress rotational shearing in the burning layer\textsuperscript{11} and may act as a restoring force.

This magnetic field argument is particularly appealing given that SAX J1808.4–3658 is the only burst oscillation source, and one of only 4 neutron stars in low-mass X-ray binaries out of over 70, that shows persistent pulsations in its non-burst emission.\textsuperscript{19–21} The absence of persistent pulsations in most of these neutron stars suggests that they lack a sufficiently strong field for the accretion flow to be magnetically channeled. Indeed, it has been proposed that the absence of persistent millisecond pulsations from most neutron stars in low-mass X-ray binaries is due to diamagnetic screening of the neutron star magnetic field by freshly accreted material for the typical range of mass accretion rates\textsuperscript{22} (M ≥ 10\textsuperscript{-10} M\textsubscript{⊙} yr\textsuperscript{-1}, where M\textsubscript{⊙} is the solar mass). In this context, we note that all four persistent millisecond X-ray pulsars lie at the low end (M ~ 10\textsuperscript{-11} M\textsubscript{⊙} yr\textsuperscript{-1}) of the mean M distribution for low-mass X-ray binaries. If this explanation is correct, then most burst oscillation sources are unlikely to show persistent pulsations.

We can measure the rotational phase of the oscillations in the burst tails. For each burst, we determined a rotational ephemeris using the persistent (accretion-powered) pulsations in the data for a few thousand seconds prior to the burst and compared this to the phase (epoch of maximum intensity) of the oscillation in the burst tail. The burst tail oscillations all had the same rotational phase within ±6% and were roughly phase-aligned with the non-burst pulsations, leading them by an average of 11% (Fig. 2). These measurements will help resolve the puzzle of why oscillations persist in the burst tail, when the nuclear burning has presumably enveloped the entire star.

Figure 1. Dynamic power spectra of millisecond oscillations in an X-ray burst on 18 October 2002 from SAX J1808.4–3658. (a) We analyzed the 2–60 keV PCA data binned at 122 µs resolution with no energy resolution, with the bin times corrected to the binary center-of-mass frame. We computed overlapping, oversampled Fourier power spectra of 2 s duration spaced at 0.25 s intervals. The contours show Fourier power levels as a function of frequency and time, and the solid histogram shows the X-ray intensity of the burst. The horizontal dotted line shows the (known) pulsar spin frequency. A rapidly drifting oscillation was detected during the burst rise. The rapid frequency drift may be an indication that SAX J1808.4–3658 has a stronger magnetic field than the other neutron stars, since a sufficiently strong field will suppress rotational shearing in the burning layer\textsuperscript{11} and may act as a restoring force.

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SARS are rare. However, RXTE has no significant selection
bias against detecting very short period millisecond
radio pulsars, and persistent millisecond X-ray pul-
sation effects against detecting very short period millisec-
ond pulsars, since there have been strong observational selec-
tion effects against detecting very short period millisecond
radio pulsars, and persistent millisecond X-ray pulsars are rare. However, RXTE has no significant selection
effects against detecting burst oscillations at frequencies
well above 1 kHz, so the nuclear-powered pulsars are ideal for
probing the fast end of the pulsar spin distribution.

The spin frequencies of the 11 nuclear-powered pulsars
lie between 270 Hz and 619 Hz, and within that range are
marginally consistent with a uniform distribution. How-
ever, the absence of spins above 619 Hz is significant. If
we make the simple assumption of a uniform spin distribu-
tion in the range [ν\text{low}, ν\text{high}]
and consider a sample of N pulsars with spin frequencies νj, then a Bayesian
analysis yields the probability density for ν\text{high} (within a
normalization factor),

\[ p(ν\text{high}) = [ν\text{high} - \min(νj)]^{1-N} - \nu_\text{high}^{1-N} \]

for ν\text{high} ≥ max(νj), where we have made an a priori al-
lowance for a 0 < ν < 3 kHz range. For the 11 observed
spins, this yields an upper limit of ν\text{high} < 760 Hz (95%
confidence) on the maximum spin frequency, which is also
consistent with the fastest known (641 Hz) millisecond ra-
dio pulsar.26 This is well below the breakup frequency for
nearly all models of rapidly rotating neutron stars (except
for those that have an extremely stiff equation of state and
contain a pion/kaon condensate in the core, and then only
for M < 1.5 M_\odot).27 Some mechanism clearly acts to halt
pulsar spin-up while accretion is still active.

Steady magnetic accretion torques should drive an ac-
creting pulsar to an equilibrium spin frequency that de-

dpends upon M and the surface dipole magnetic field B. Taking the M range observed in the nuclear-powered pul-
sars and the disk-magnetosphere interaction models rele-
vant for weakly magnetic neutron stars,28 magnetic spin
 equilibrium can account for the observed spin distribution
if all these systems have B ∼ 10^{8} G, consistent with the
field inferred in SAX J1808.4−3658 (ref. 28) and in the
millisecond radio pulsars.29 However, fields this strong
should be dynamically important for the accretion flow,
making it difficult to understand the lack of persistent
pulsations in the non-burst emission of all the nuclear-
powered pulsars other than SAX J1808.4−3658 and in-
stead suggesting a broader range of field strengths. Al-
ternatively, several authors have shown that gravitational
radiation can carry away substantial angular momentum
from accreting neutron stars, driven either by the excitation
of an r-mode instability in the neutron star core7,9 or by a rotating, accretion-induced crustal quadrupole mo-
ment.8 These losses can balance accretion torques for the
relevant ranges of ν and M, and the predicted gravita-
tional radiation strengths are near the detection threshold
for planned gravitational wave interferometers, especially
in the case where an X-ray timing ephemeris is available.30

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Figure 2. Relative phase of the burst tail oscillations in
SAX J1808.4−3658 and the persistent accretion-powered
distributions just prior to the burst, for all four bursts. The
histograms show the profile of the persistent pulsations,
and the dashed lines indicate the rotational phase of the
burst tail oscillations. The oscillations all have nearly the
same rotational phase and slightly lead the persistent pul-
sations.

The phase locking indicates that the oscillations are asso-
associated with the stellar surface and suggests that the emitting “hot spot” has a nearly fixed orientation with respect
to the pulsar’s magnetic axis. The 11% offset is consistent
with the phase drift accumulated over the duration of the
burst tails due to the slight (<0.002%) frequency differ-
ence of the burst oscillations and the non-burst pul-
sations, but this requires an initial phase alignment in the
burst tail followed by slight motion of the hot spot.23

Our observations clearly show that brightness oscil-
lations in the tails of thermonuclear X-ray bursts are a
nearly exact tracer of stellar spin, establishing these neu-
tron stars as nuclear-powered pulsars. (Other recent ob-
servations show that the kHz QPO frequency separation
in this neutron star is half the spin frequency,4 verify-
ing that the burst oscillation traces the spin and not a
harmonic.) This provides a powerful tool for studying the
most rapidly rotating neutron stars. It is believed that accretion from a binary companion is required in or-
der to spin up old neutron stars to millisecond periods.1
For sustained accretion in the absence of another angular
momentum sink, this process is limited only by the neu-
tron star breakup frequency, up to 3 kHz depending upon
the nuclear equation of state.24,25 It has been difficult to
determine the actual spin distribution of millisecond
pulsars, since there have been strong observational selec-
tion effects against detecting very short period millisecond
radio pulsars, and persistent millisecond X-ray pulsars are rare. However, RXTE has no significant selection

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