Discovery of the first accretion-powered millisecond X-ray pulsar

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The precise origins of the millisecond radio pulsars, discovered in the early 1980s\textsuperscript{1}, remain uncertain until this day. They plausibly evolve from accreting low magnetic-field neutron stars in X-ray binary systems\textsuperscript{2,3}. If so, these stars should spin at millisecond rates. In accordance with this idea, quasi-periodic oscillations discovered in X-ray binaries around 50 Hz\textsuperscript{4} and 1 kHz\textsuperscript{5,6}, and drifting oscillations at several 100 Hz in X-ray bursts\textsuperscript{6} have all been interpreted in terms of millisecond spins of weakly magnetized neutron stars\textsuperscript{7,8}. However, in 15 years of searching\textsuperscript{9,10,11,12}, the expected coherent millisecond signals from X-ray binaries remained elusive. In this Letter, we report the discovery\textsuperscript{13} of the first example of such a signal. Using the Rossi X-ray Timing Explorer we find persistent 2.49 millisecond X-ray pulsations in an X-ray binary, which we interpret to come from an accretion-powered millisecond X-ray pulsar in the system. This is the first known object of its kind. It is likely to switch on as a millisecond radio pulsar when the accretion turns off completely. The source is positionally coincident\textsuperscript{14,13} with the known transient X-ray burster SAX J1808.4–3658\textsuperscript{15}, which also makes this the first X-ray pulsar which exhibits thermonuclear X-ray bursts.

The transient X-ray burster SAX J1808.4–3658 was discovered in September 1996 with the Wide Field Cameras onboard BeppoSAX\textsuperscript{15}. Two thermonuclear X-ray bursts were observed, and the source was classified as a low-mass X-ray binary (LMXB) at a probable distance of 4 kpc\textsuperscript{15}. Recently, a transient source, positionally coincident with SAX J1808.4–3658 to within a few arcmin, was detected\textsuperscript{14} with the Proportional Counter Array (PCA) onboard the Rossi X-ray Timing Explorer (RXTE), showing the source was again in outburst. The 2–10 keV flux on 1998 April 11 was $1.5 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$.

Data with a time resolution of 1/8192 s were taken with the PCA on 1998 April 11. The 2–60
keV count rate varied between 892 and 1007 counts/sec, including a \(\sim 130\) c/s background; no X-ray bursts were observed. We computed a power spectrum of \(\sim 3000\) s of X-ray data. The spectrum clearly shows the X-ray pulsations near a frequency of 401 Hz (Fig. 1). Their amplitude was \(\sim 4.1\%\) (rms) in the 2–60 keV range, with little dependence on photon energy.

We then divided the data into 128 second segments and determined the pulsation frequency in each segment by an epoch folding technique. The signal was present in each segment. During our initial 2-hr observing span the pulsation frequency showed a smooth, approximately sinusoidal \(\sim 110\)-min variation between 400.986 and 401.022 Hz in the satellite frame. We corrected for this smooth variation and found we could coherently fold the pulsations. Attributing the smooth frequency variation to Doppler shifts, in part due to the satellite motion, we concluded that the intrinsic coherence of the signal exceeded \(10^6\), leaving no other interpretation than the presence of a millisecond X-ray pulsar in the system\(^{13}\). We confirmed the presence of the signal in later observations taken between 1998 April 13–18. The Doppler shifts clearly show up in a dynamical power spectrum (Fig. 2).

The folded pulse profile (Fig. 3) is near-sinusoidal, with amplitudes of the harmonics at 2 and 3 times the 401 Hz frequency of \(\sim 11\) and \(\sim 4\%\) of the 401 Hz amplitude, respectively. This is similar to what is observed\(^{16}\) in the 0.5 sec pulsar GRO J1744–28 and might be related to both systems having a low inclination. It is possible that the spin period is 4.98 ms with two near-identical pulses per cycle. However, folding at this period indicates no significant difference in shape between the odd and even pulses. The folded light curves in the 2–5.0, 5.0–8.6 and 8.6–60 keV photon energy bands are not significantly different.

Below 100 Hz the power spectrum somewhat resembles that of other accretion-powered X-ray
pulsars as well as of low-luminosity LMXBs. There is a strong (\sim20\% rms, 2–60 keV) broad noise component below 100 Hz, with a bump near 12 Hz that, when interpreted in terms of the magnetospheric beat-frequency model would suggest an inner disk radius of 30 km (just inside the corotation radius). An additional \sim17\% (rms) noise component extends out to roughly the 0.4 kHz pulse frequency. This is not commonly seen in LMXBs, but is, at proportionally lower cutoff frequencies, in other accreting pulsars. No kilohertz quasi-periodic oscillations are detected. However, upper limits (3–6\% rms), when compared to observed amplitudes in other LMXBs, are as yet insufficient to exclude their presence.

The detection of the pulsations from an X-ray transient that, moreover, likely showed thermonuclear X-ray bursts during an earlier outburst, identify this X-ray pulsar as one that is powered by accretion from a binary companion, and pulses because magnetically channeled accretion produces hot spots on the neutron star surface which spin around with the star’s spin. In a subsequent analysis Chakrabarty and Morgan have found that, correcting for the satellite orbit, the pulsar’s Doppler shifts indicate it is in a 2-hr orbit around a low-mass star, with an intrinsic pulse frequency of 400.9753(1) Hz.

For accretion to proceed uninhibited by the centrifugal force on the accreting matter corotating in the magnetosphere, the magnetic field strength \( B \) of this pulsar must be much lower than the \sim10^{12} Gauss typical for slower X-ray pulsars. Centrifugal inhibition occurs when the magnetospheric radius \( r_M = 18\text{km} \xi \mu_{26}^{4/7} m_{1/7} R_6^{-2/7} L_{37}^{-2/7} \) is larger than the corotation radius \( r_{\text{co}} = 15\text{km} m^{1/3} P_{1\text{ms}}^{2/3} \), where \( \mu_{26} \) is the magnetic moment in \( 10^{26} \) Gauss cm\(^3\), \( L_{37} \) the bolometric luminosity in \( 10^{37} \) erg/s, \( m \) the neutron star mass in solar masses, \( R_6 \) its radius in units of \( 10^6 \) cm, \( \xi \) a dimensionless factor that is probably between 0.5 and 1, and \( P_{1\text{ms}} \) the spin period in ms. On 1998 April 11 the 2–10 keV luminosity, assuming a distance of 4 kpc, was \sim 3 \times 10^{36} \text{ erg s}^{-1}. The spectrum is quite
hard\textsuperscript{22}, and the bolometric luminosity may have been closer to $6 \times 10^{36}$ erg s$^{-1}$. With the above expressions this leads to an upper limit on $B$ of $\sim 2 - 6 \times 10^8$ Gauss ($4 - 14 \times 10^8$ Gauss if the pulse period is 4.98 ms). As the X-ray flux decreases in the transient decay this upper limit will become less. When centrifugal inhibition sets in we might see a rapid drop in X-ray flux\textsuperscript{23,24}; this would allow to estimate the value of $B$.

Such a low magnetic field strength is in the range of values inferred for millisecond radio pulsar\textsuperscript{25}. The object appears to be located above the pulsar “death line”\textsuperscript{25}, so when accretion finally turns off, this source would likely switch on as a radio pulsar. This might even happen between X-ray outbursts, if the density in the pulsar environment, at least out to the light cylinder at 120 km, drops sufficiently. So, this low-mass X-ray binary could indeed be one of the progenitors of the millisecond radio pulsars, and it might be an intermittent radio pulsar now.

That this pulsar likely also bursts is in accordance with theoretical expectations. Normally, X-ray bursts do not occur in accreting pulsars, as due to the magnetic field either the nuclear burning takes place steadily\textsuperscript{26}, or nuclear burning fronts can not propagate rapidly\textsuperscript{27}. However, if the field is weak, these mechanisms are ineffective and bursts could occur\textsuperscript{21}. This seems to be verified by SAX J1808.4–3658. This is the first time pulsations and thermonuclear burst are seen in one source. The bursts in the 0.5 s pulsar GRO J1744–28\textsuperscript{16,28} are not thermonuclear but due to accretion instabilities\textsuperscript{28,29}.

As the likely $B$ field of SAX J1808.4–3658 is not much different from that inferred for other LMXBs from models for the rapid aperiodic variability\textsuperscript{7} and the X-ray spectra\textsuperscript{30}, and its spin rate is similar to that inferred in other LMXBs from models for burst oscillations\textsuperscript{6} and kHz QPOs\textsuperscript{8} the question arises: Why is SAX J1808.4–3658 the only known LMXB with a millisecond pulsar? While
it can not be excluded that at higher luminosity SAX J1808.4–3658, like the other LMXBs, would not pulse, for LMXBs of similar luminosity the simplest explanation would seem to be that their $B$ fields are considerably weaker than that of this pulsar. It would be of great interest to detect in SAX J1808.4–3658 the drifting oscillations during X-ray bursts interpreted in other LMXBs as due to the neutron star spin$^6$, or the twin kHz QPO peaks whose frequency difference has also been interpreted as the neutron star spin frequency$^{5,6,8}$, as the fact that the spin frequency of SAX J1808.4–3658 is known will provide a direct test of these interpretations.

We finally note that the high-precision timing measurements possible due to the high frequency of these pulsations will allow to study the torques of the accreting matter on the neutron star and the star’s response to these torques with unprecedented accuracy. Moreover, for the first time this will be possible in an accretion flow that extends freely down to only a few tens of kilometers from the neutron star surface. It is likely that this will provide new insights into the nature of the inner accretion flows around weakly magnetized compact objects. It may also provide new information about the internal constitution of neutron stars.
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Fig. 1.— Leahy\textsuperscript{9} normalized power spectrum of the 1998 April 11 20:38–21:21 UT persistent emission of SAX J1808.4–3658. The periodicity near 401 Hz is obvious. No harmonics or subharmonics are seen.
Fig. 2.— Dynamical power spectrum of the 1998 April 11–18 data. The Doppler shifts in pulsation frequency due to the satellite and pulsar orbital motion are evident. Time axis is not contiguous; vertical lines indicate data gaps.
Fig. 3.— The 2–60 keV light curve folded at the 2.49 ms period. Two cycles are plotted for clarity. The solid line is the best fit sinusoid.