Part 9

Population and Neutron Star Properties

Section C. Accreting Systems

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Recycling in progress: RXTE discovery of the first accretion-powered millisecond pulsar

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Abstract. The discovery is reported of the first accretion-powered millisecond pulsar, SAX J1808.4–3658. This 2.5 millisecond pulsar has a magnetic field strength of 1–10 10^8 Gauss and has all the characteristics of the long-predicted millisecond radio pulsar progenitor, a neutron star in an X-ray binary system where the process of recycling is taking place at this time.

1. Introduction

When the Rossi X-ray Timing Explorer (RXTE) was launched on December 30, 1995 it was hoped that the long-anticipated accretion-powered (X-ray) millisecond pulsars would now, finally, be found in X-ray binaries. Magnetospheric disk accretion theory indicates that the transfer of angular momentum from an accretion disk to a low-magnetic field neutron star necessarily leads to such rapid spin frequencies, and disk-accreting low-magnetic field neutron stars are common in the bright low-mass X-ray binary systems which are a prime target for RXTE. The rotation-powered millisecond pulsars are thought to be produced in such accreting systems by accretion-induced spin-up, a process known as "recycling" (e.g. Bahttacharya and van den Heuvel 1991). Yet, despite numerous searches (e.g., Leahy et al. 1983, Mereghetti and Grindlay 1987, Wood et al. 1991, Vaughan et al. 1994) such rapid pulsars had not turned up in observations of LMXBs.

What happened instead is that RXTE in the first two years of its active life discovered several other exciting millisecond time variability phenomena in low-mass X-ray binaries (see van der Klis 2000 for a review): kilohertz quasi-periodic oscillations which are thought to be a diagnostic of the very rapid (millisecond time scale) orbital motions in the inner accretion disks around the neutron stars in these systems, and the short-lived burst oscillations, with slightly drifting frequencies in the 300–600 Hz range, which are probably caused by transient hot spots on the neutron-star surface originating in the thermonuclear burning process. True accretion-powered millisecond X-ray pulsars remained elusive, until finally, the first (and up to now, only) one was discovered by Rudy Wijnands using RXTE on April 13, 1998 in the soft X-ray transient SAX J1808.4–3658 (Wijnands and van der Klis 1998a,b).

2. SAX J1808.4−3658: a millisecond radio pulsar progenitor

The pulse frequency of SAX J1808.4−3658 is 401 Hz, and the signal is quite unmistakable (Fig. 1). This 2.5 millisecond pulsar is at the same position as the transient X-ray source that burst out in September 1996 and gave the object its name (discovered with BeppoSAX; in 't Zand et al. 1998). As in this outburst the transient showed two type 1 X-ray bursts, SAX J1808.4−3658 is also the first genuine bursting pulsar, breaking the long-standing rule (e.g., Lewin & Joss 1981) that pulsations and type 1 X-ray bursts are mutually exclusive.

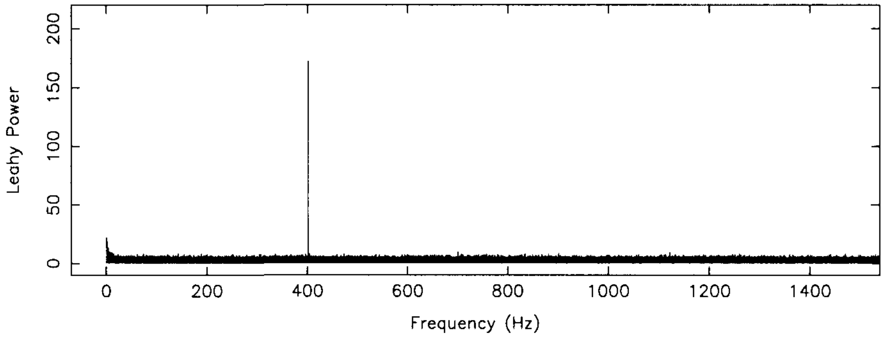

Figure 1. The discovery power spectrum of the first accreting millisecond X-ray pulsar. (Wijnands and van der Klis 1998b)

For a magnetized neutron star that is spinning this fast to be able to accrete, its magnetic field must be relatively weak. Otherwise, the radius of the magnetosphere exceeds the corotation radius, and matter corotating in the magnetosphere can not overcome the centrifugal barrier. With the 2.5 ms spin period this constraint leads to upper limits on the magnetospheric radius of 31 km, and, with standard magnetospheric models, on the surface field strength of 2–6 10^8 Gauss (Wijnands & van der Klis 1998b). A similarly simple estimate, involving in addition the requirements that for pulsations to occur the radius of the magnetosphere must be larger than the radius of the neutron star, and that both constraints on magnetospheric radius must be satisfied over the full range in luminosity in which SAX J1808.4−3658 was seen to pulse, would constrain the star's radius to $< 13.8\,\mathrm{km}\ M/M_\odot$ (Burderi & King 1998) and hence put strong limits to the equation of state of supranuclear-density matter.

However, the process of accretion onto a neutron star with such a low magnetic field is different from that in classical, 10^{12}-Gauss accretion-powered pulsars. The model for the disk flow that should be used in calculating the magnetospheric radius is different this close to the neutron star, the structure of the disk-star boundary layer may be different, and multipole components in the magnetic field can become important. It could even be the case that a classical magnetosphere does not form and the (5%) modulation at the star's spin frequency arises due to milder effects of the magnetic field on either the flow pattern or the emission characteristics. Psaltis & Chakrabarty (1999) provide a critical discussion of these and other uncertainties and conclude that the magnetic field strength is (1–10) 10^8 Gauss, which puts the source right among the millisecond radio pulsars (Fig. 2). It is likely that when the accretion shuts off sufficiently for the radio pulsar mechanism to be able to operate, the system will show up as a binary millisecond radio pulsar; this is expected to happen at the end of the system's life as an X-ray binary, i.e., SAX J1808.4−3658 is indeed a millisecond radio pulsar progenitor. Such a radio turn-on might also occur in between the transient outbursts (Wijnands and van der Klis 1998b). However, so far radio observations have not detected the source in X-ray quiescence (Gaensler et al. 1999).

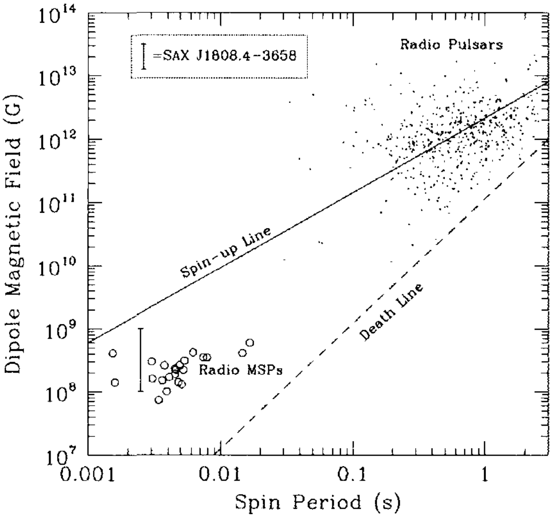

Figure 2. The position of SAX J1808.4−3658 in the radio-pulsar period vs. magnetic-field diagram. (Psaltis & Chakrabarty 1999)

3. Discussion

Now that this Holy Grail has finally been found and one accreting millisecond pulsar is known, of course, the question becomes "why only one?". The pulsations in SAX J1808.4−3658 are not particularly weak and we know for sure that pulsars of similar amplitude and observed (as opposed to intrinsic) coherence are not present in many other LMXBs observed in a similar (rather standard) way as SAX J1808.4−3658 was with RXTE. The answer to this question may lie in part in the orbital characteristics of the source. Its 2.0-hr orbital period was discovered, and the orbit measured, by Chakrabarty and Morgan (1998a,b; Fig. 3). With a projected orbital radius $a \sin i$ of only 63 light *milli*seconds and a mass function of $3.8\,10^{-5}M_{\odot}$, the companion is either very low mass, or we are seeing the orbit nearly pole-on.

If we see the orbit pole-on, then this may be what allows us to see the pulsations in this system, and a different orientation of the orbit what hides them in many other LMXBs. The fact that the pulse profile of SAX J1808.4−3658 (Fig. 4) is nearly sinusoidal might be related to this pole-on orientation. In

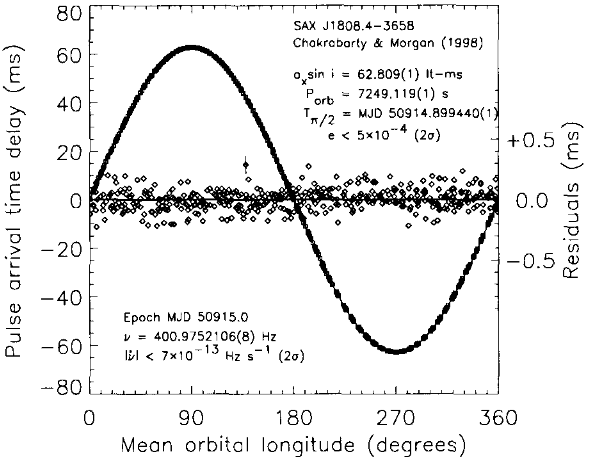

Figure 3. The radial velocity curve and orbital elements of SAX J1808.4−3658 (Chakrabarty and Morgan 1998b).

any case, of course, the low radial-velocity amplitude of the orbit reduces the Doppler shifts and keeps the pulsar more nearly coherent, facilitating its discovery without the use of special deacceleration techniques (which are, however, being used to try and discover other pulsars; e.g., Vaughan et al. 1994; Jonker et al. 2000).

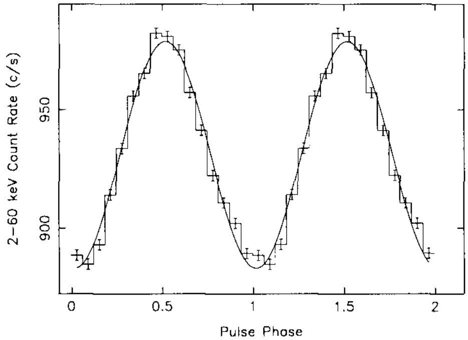

Figure 4. The pulse profile of SAX J1808.4−3658. (Wijnands and van der Klis 1998b)

Another possibility is that SAX J1808.4−3658 is a different type of system from the other well-studied LMXBs. Perhaps the fact that it is an unspectacular little transient is related to an accretion history that favours the preservation of a magnetic field configuration (strength, orientation) that produces a pulsar, and some *other* unspectacular little transients (with, perhaps, low-mass companions) will turn out to be millisecond pulsars as well. However, searches along these lines inspired by the case of SAX J1808.4−3658 have not so far yielded any additional millisecond X-ray pulsars.

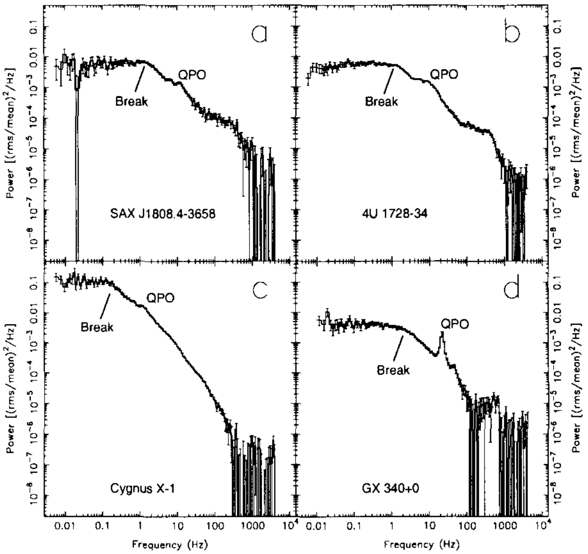

Figure 5. Broad-band power spectra of, respectively, the millisecond pulsar, an atoll source, a black-hole candidate and a Z source. (Wijnands and van der Klis 1999a)

Apart from its pulsations, SAX J1808.4−3658 actually appears to be quite similar to other LMXBs. Wijnands and van der Klis (1999a) point out, that the similarity in the power spectra of black-hole candidates and low-luminosity low-magnetic-field neutron stars found with EXOSAT and Ginga (van der Klis 1994) also holds for SAX J1808.4-3658. The power spectra look very similar (Fig. 5). Nearly always there is a break at low frequency and a QPO-like feature above the break. The correlation between the break frequency and the QPO frequency is excellent (Fig. 6), and encompasses both neutron stars and black-hole candidates. The X-ray spectral properties (Heindl & Smith 1998, Gilfanov et al. 1998) of SAX J1808.4−3658 are also very similar to those of other LMXBs at low accretion rate.

So, either the neutron stars in SAX J1808.4−3658 and these other LMXB systems have similar magnetic fields, or the fields are different but the size of the small magnetosphere does not appreciably affect the spectral and slow-variability characteristics. In the latter case, the conclusion seems warranted that these characteristics are mainly determined in the disk outside the magnetosphere. If the black holes are really part of the same scheme, this conclusion is strenghtened. Then spin-orbit beat-frequency models and any other models for the low-frequency timing phenomena or the energy spectra spectra requiring a material surface, an event horizon, a magnetic field, or their absence, would be excluded.

It would be of enormous interest to find burst oscillations or kHz QPOs in SAX J1808.4−3658, as this would allow right away to confirm or reject various models for these phenomena involving the neutron star spin, which in SAX J1808.4−3658, uniquely among accreting low-magnetic field neutron stars,

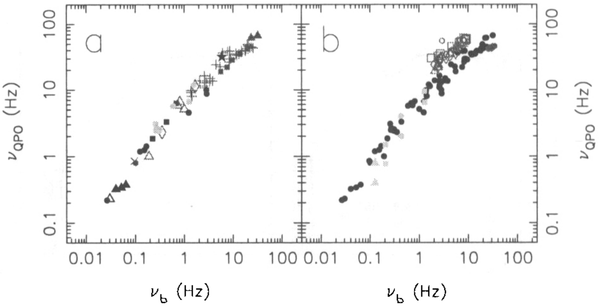

Figure 6. Relation between noise break frequency and QPO frequency for sources of the types shown in the previous figure. (Wijnands and van der Klis 1999a)

is known accurately and with certainty. However, the RXTE observations during the first few days of the April 1998 outburst, when the source was brightest, were relatively limited. Perhaps for this reason, although SAX J1808.4−3658 is known to be a type 1 X-ray burster, no bursts were seen in the RXTE observations of the April 1998 outburst, nor were kHz QPOs detected. Early in the outburst, when from comparing to other LMXBs the chances of seeing kHz QPOs were best, due to the limited observing time RXTE was not very sensitive to them (Wijnands and van der Klis 1998c). Longer RXTE observations have been planned for the next outburst of SAX J1808.4−3658.

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