The two-hour orbit of a binary millisecond X-ray pulsar

Deepto Chakrabarty & Edward H. Morgan

Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

Typical radio pulsars are magnetized neutron stars that are born rapidly rotating and slow down as they age on time scales of 10 to 100 million years. However, millisecond radio pulsars spin very rapidly even though many are billions of years old.\(^1\) The most compelling explanation is that they have been “spun up” by the transfer of angular momentum during accretion of material from a companion star in so-called low-mass X-ray binary systems, LMXBs. (LMXBs consist of a neutron star or black hole accreting from a companion less than one solar mass.\(^2\)) The recent detection of coherent X-ray pulsations with a millisecond period from a suspected low-mass X-ray binary system appears to confirm this link.\(^3\) Here we report observations showing that the orbital period of this binary system is two hours, which establishes it as an LMXB. We also find an apparent modulation of the X-ray flux at the orbital period (at the two per cent level), with a broad minimum when the pulsar is behind this low-mass companion star. This system seems closely related to the “black widow” millisecond radio pulsars, which are evaporating their companions through irradiation.\(^4\) It may appear as an eclipsing radio pulsar during periods of X-ray quiescence.

The transient X-ray source SAX J1808.4–3658 was first observed in September 1996 by the Wide Field Cameras on the BeppoSAX X-ray satellite during a bright state which lasted about 20 days.\(^9\) The source was not detected (X-ray flux \(< 3 \times 10^{−11}\) erg cm\(^−2\) s\(^−1\) in the 2–10 keV band) during an August 1996 observation, but reached a peak X-ray flux of \(2 \times 10^{−9}\) erg cm\(^−2\) s\(^−1\) during the September bright state. Also during the bright state, BeppoSAX detected two type I X-ray bursts from the source, each lasting less than 30 s. Such bursts are due to thermonuclear ignition of accreted material on the neutron star's surface that have low (<10\(^{10}\) G) magnetic fields.\(^10\) Analysis of the bursts in SAX J1808.4–3658 indicates that it is 4 kpc distant and has a peak X-ray luminosity of \(6 \times 10^{36}\) erg s\(^−1\) in its bright state and \(< 10^{35}\) erg s\(^−1\) in quiescence.\(^9\) The source position was determined to within a 1\(σ\) radius of 0.6 arcmin.

More recently, a serendipitous slew of the Proportional Counter Array (PCA) on the Rossi X-ray Timing Explorer (RXTE) over this region of the sky on 9 April 1998 indicated the presence of an X-ray source, designated XTE J1808–369. Repeated scans over the region with the PCA on 11 April localized the position with sufficient precision to confirm that the source was probably the same as SAX J1808.4–3658.\(^11\) RXTE subsequently made numerous pointed observations of the source during 11 April–6 May on a public “target-of-opportunity” basis. The source reached a peak luminosity of \(5 \times 10^{36}\) erg s\(^−1\) on 13 April and had faded below \(10^{35}\) erg s\(^−1\) by 6 May.

Strong coherent 400 Hz pulsations were clearly detected in the 2–30 keV PCA data from most of these observations, and were first reported by Wijnands and van der Klis.\(^12,3\) These are the fastest persistent coherent pulsations ever detected from an X-ray binary. From standard magnetic disk accretion theory, the detection of X-ray pulsations at a luminosity \(\sim 10^{36}\) erg s\(^−1\) requires that the neutron star’s surface dipole magnetic field be \(B < 10^8\) G (ref. 3). This is much weaker than the \(\sim 10^{12}\) G fields found in other (slower) accretion-powered pulsars,\(^13\) but it is consistent with the weak fields expected for type I X-ray bursters.\(^10\) If pulsations are detected when the source is at lower luminosities, the implied surface field would be even weaker.

In order to search for orbital Doppler shifts, we first selected the 3–30 keV photon arrival times during 11–18 April and binned them into \(2^{−11}\) s (≈0.5 ms) samples, after correcting these times for RXTE’s motion with respect to the solar system barycenter using the best BeppoSAX position for the source\(^9\) (right ascension 18h 08m 29s, declination −36° 58.6′, equinox J2000.0). We then measured the barycentric pulse frequency at 128 s intervals using an oversampled Fourier power spectrum. The sequence of pulse frequencies showed an obvious 2 hr sinusoidal modulation which was well fit by a constant spin frequency plus a circular, Keplerian orbit.\(^14\)

Using this provisional timing model, we epoch-folded each 128 s interval in the 11–18 April data and cross-correlated the resulting pulse profiles with a sinusoid to measure the pulse phase history, which generally yields more precise timing parameters than a pulse frequency...
Table 1. Observed parameters of SAX J1808.4–3658

| Parameter                        | Value     |
|----------------------------------|-----------|
| Barycentric pulse frequency, $\nu_0$ (Hz) | 400.9752106(8) |
| Pulse frequency derivative, $|\dot{\nu}|$ (Hz s$^{-1}$)        | $< 7 \times 10^{-13}$ |
| Projected semimajor axis, $a_1 \sin i$ (lt-ms) | 62.809(1) |
| Orbital period, $P_{\text{orb}}$ (s) | 7249.119(1) |
| Epoch of 90° mean longitude, $T_{\text{m}/2}$ (MJD) | 50914.899440(1) |
| Eccentricity, $e$               | $< 5 \times 10^{-4}$ |
| Pulsar mass function, $f_1$ ($M_\odot$) | 3.7789(2) $\times 10^{-5}$ |
| Modified Julian date MJD = JD − 2400000.5. | Numbers in parentheses are the 1σ uncertainties in the last significant figure, and upper limits are quoted at the 2σ level. The $\dot{\nu}$ limit refers to the magnitude, independent of sign. Epochs are given in Barycentric Dynamical Time (TDB). |

The pulsar mass function $f_1$, which relates the pulsar mass $m_1$, the companion mass $m_2$, and the binary inclination $i$ (the angle between the line of sight and the orbital angular momentum vector), may be computed from the observed Keplerian parameters $a_1 \sin i$ and $P_{\text{orb}}$, with $P_{\text{orb}}$ given in Barycentric Dynamical Time (TDB).

$$f_1 \equiv \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} = \frac{4\pi^2(a_1 \sin i)^3}{GP_{\text{orb}}^2}, \quad (1)$$

from which we find $f_1 = 3.7789(2) \times 10^{-5}$ $M_\odot$ (here $M_\odot$ is the solar mass). Given assumed values of $m_1$ and $i$, equation (1) can be solved for $m_2$. For $m_1$, dynamical mass measurements in both binary millisecond radio pulsars and accretion-powered pulsars are all generally consistent with a neutron star mass of $1.35 \, M_\odot$. However, neutron stars in LMXBs have undergone substantial accretion from their binary companion and may be as massive as $2 \, M_\odot$ (e.g., ref. 20). For $i$, we note that for an ensemble of binaries whose inclinations are distributed randomly, the a priori probability of observing a system with inclination $i$ or smaller is $(1 - \cos i)$. If SAX J1808.4–3658 is drawn from such an ensemble, then there is a 95% probability that $m_2 < 0.14 \, M_\odot$ if $m_1 = 1.35 \, M_\odot$. For $m_1 = 2 \, M_\odot$, we find $m_2 < 0.18 \, M_\odot$. In either case, the binary separation is most likely of order 1 lt-s.

The nature of the companion star provides an important clue to the evolutionary history of an LMXB. The only direct information we have on the companion comes from observations of the probable optical counterpart, which suggest that the companion is a faint low-mass star subject to X-ray heating by the pulsar. We can use the binary parameters to deduce more about this star. The companions in most LMXBs fill (or nearly fill) their critical gravitational potential surface, known as the Roche lobe. Because the mean density of a Roche-lobe–filling companion (for the case where $m_2 < m_1$) is uniquely determined by the binary period, we can relate the companion’s radius in SAX J1808.8–3658 to its mass as $R_2 = 0.17 \, R_\odot (m_2/0.1 \, M_\odot)^{1/3}$, giving a minimum companion radius of 0.12 $R_\odot$ (here $R_\odot$ is the solar radius). The assumption of Roche lobe overflow thus strongly constrains the nature of the companion. Given the compact size of the binary, only white dwarf (WD) or low-mass main sequence (MS) companions are plausible. (In principle, a helium-burning star could also fit in this binary, but we would expect it to be much brighter than the proposed optical counterpart.) A WD with mass $m$ has radius $R = 0.013 \, R_\odot (1 + X)^{5/3} (m/M_\odot)^{-1/3}$, where $X$ is the hydrogen mass fraction. Comparing this to our equation for $R_2$, we see that a helium WD ($X = 0$) would be too...
small, and hence is ruled out. Even a hydrogen-rich WD 
($X = 0.9$) is essentially excluded for all but $i \approx 90^\circ$. How-
ever, the lack of a deep X-ray eclipse rules out $i > 82^\circ$, 
assuming a Roche-lobe–filling companion.

Normal low-mass hydrogen MS stars have $R/R_\odot \approx m/M_\odot$, 
and comparison of detailed models with our equation for $R_2$ yields 
a Roche-lobe–filling mass of 0.17 $M_\odot$. This would require 
a small binary inclination ($i < 20^\circ$), which has low a priori 
probability (5%). However, normal MS models are inappropriate 
in our case, since the stellar structure must be strongly influenced 
by irradiation from the pulsar. If the incident flux at the 
companion surface exceeds $\sim 10^{10}$ erg cm$^{-2}$ s$^{-1}$, the star may 
be “bloated” to larger radii. This is especially true for 
MS stars having $m < 0.3 M_\odot$, which have fully convexive 
envelopes. For the ~1 lt-s binary separation in this 
system, the X-ray flux at the companion will exceed $10^{14}$ 
erg cm$^{-2}$ s$^{-1}$, and the bloating can be severe. Under 
these conditions, MS stars as light as 0.1 $M_\odot$ or less may fill 
their Roche lobe, consistent with a more likely inclination.

Another possibility is that irradiation by the neutron 
star might directly drive mass loss from the companion 
(“ablation”) whether or not it fills its Roche lobe. The 
binary parameters of SAX J1808.4–3658 are very similar 
to those of the five “black widow” millisecond radio pulsars 
in very close binaries, all of which are ablating their 
low mass companions. At least four of these radio systems 
show eclipses which are too broad to be caused by a 
Roche-lobe–filling companion, and which are instead 
attributed to an ablated wind.

We find evidence that the X-ray flux from SAX 
J1808.4–3658 is slightly modulated at the orbital period. 
The apparent modulation is roughly sinusoidal with 2% 
amplitude and a minimum when the pulsar is behind 
the companion, and it is much broader and much shallower 
than the (at most) 5 minute eclipse possible from a Roche-
lobe–filling companion. However, the detailed features of 
this 2 hr modulation must be viewed with caution, since 
its strength is comparable to the variation of the RXTE 
background with the 96 min spacecraft orbit. The 
similarity in strength and time scales of these two variations 
makes them difficult to disentangle, and final confirma-
tion must await either additional data or an improvement 
in the RXTE background model. Still, the detection of a 
2 hr source flux modulation (if not its precise morphology) 
seems secure.

We suggest that the intensity dips are due to scattering 
in an ablated wind. Given the similarity between this 
source and the eclipsing radio pulsars, SAX J1808.4–3658 
may emerge as a radio pulsar during X-ray quiescence. 
Moreover, since the radio emission would be less pene-
trating than the X-rays, a deeper eclipse dip might be 
oberved, possibly providing a strong constraint on the 
binary inclination. The presence of the slight X-ray dips, 
if confirmed, would rule out small binary inclinations and 
make it highly likely that the companion mass is less than 
0.1 $M_\odot$.

Whether the mass accretion is fed by Roche-lobe over-
flow or an ablated wind or both, we can understand the 
transient nature of the X-ray emission as long as some 
of this material forms an accretion disk. Although the in-
stantaneous mass accretion rate during the 1996 and 1998 
bright states was $\approx 3 \times 10^{-10} M_\odot$ yr$^{-1}$, the small duty 
cycle of the X-ray activity indicates a long-term mean 
mass transfer rate of $\dot{M} \approx 1 \times 10^{-11} M_\odot$ yr$^{-1}$. For such 
a low $\dot{M}$, the accretion disk would probably be subject 
to dwarf-nova–type instabilities, leading to episodic out-
bursts of X-ray emission. We note that for a Roche-
lobe–filling companion, angular momentum losses due to 
gravitational radiation would drive a mass transfer rate of 
$\approx 10^{-11} M_\odot$ yr$^{-1}$ for a 0.05 $M_\odot$ secondary, consistent 
with our inferred inclination constraints.

Future X-ray outbursts from SAX J1808.4–3658 may 
allow detection of a spin frequency derivative, which would 
urther constrain both the mass accretion rate and the pul-
sar’s magnetic field strength and would provide a probe of 
magnetic disk accretion torque theory in the previously 
explored regime of a very small magnetosphere. The 
characteristic accretion torque expected for the observed 
X-ray luminosity should cause a $\nu$ of order $10^{-14}$ Hz s$^{-1}$, 
which is detectable in observations spanning a month or 
more. Further observations may also detect orbital pe-
riod evolution, which would probe the competing effects 
of gravitational radiation, tidal interactions, and mass loss 
on the binary angular momentum. An astrophysically 
interesting limit of $|P_{\text{orb}}| < 10^{-11}$ could be reached in less 
than a year of observations.
9. in ’t Zand, J. J. et al. Discovery of the X-ray transient SAX J1808.4−3658, a likely low-mass X-ray binary, *Astr. Astrophys.* **331**, L25–L28 (1998).

10. Lewin, W. H. G., van Paradijs, J. & Taam, R. E. in *X-Ray Binaries* (eds Lewin, W. H. G., van Paradijs, J. & van den Heuvel, E. P. J.) 175–232 (Cambridge Univ. Press, Cambridge, 1995).

11. Marshall, F. E. SAX J1808.4−3658 = XTE J1808−369, *IAU Circ.* , No. 6876 (1998).

12. Wijnands, R. & van der Klis, M. SAX J1808.4−3658 = XTE J1808−369, *IAU Circ.* , No. 6876 (1998).

13. White, N. E., Nagase, F. & Parmar, A. N. in *X-Ray Binaries* (eds Lewin, W. H. G., van Paradijs, J. & van den Heuvel, E. P. J.) 1–57 (Cambridge Univ. Press, Cambridge, 1995).

14. Chakrabarty, D. & Morgan, E. H. SAX J1808.4−3658 = XTE J1808−369, *IAU Circ.* , No. 6877 (1998).

15. Lyne, A. G. & Graham-Smith, F. *Pulsar Astronomy.* (Cambridge U. Press, Cambridge, 1990).

16. Roche, P. et al. SAX J1808.4−3658 = XTE J1808−369, *IAU Circ.* , No. 6885 (1998).

17. Giles, A. B., Hill, K. M. & Greenhill, J. G. SAX J1808.4−3658 = XTE J1808−369, *IAU Circ.* , No. 6886 (1998).

18. Thorsett, S. E. & Chakrabarty, D. Neutron star mass measurements. I. Radio pulsars., *Astrophys. J.* , submitted [astro-ph/9803260] (1998).

19. van der Klis, M. & van Paradijs, J. & Zuiderwijk, E. J. On the masses of neutron stars, *Astr. Astrophys.* **303**, 497–501 (1995).

20. Zhang, W., Strohmayer, T. E. & Swank, J. H. Neutron star masses and radii as inferred from kilohertz quasi-periodic oscillations, *Astrophys. J.* , L167–L170 (1997).

21. Flannery, B. P. & Warner, B. Ultrashort-period binaries. II. HZ 29 (=AM CVn): a double-white-dwarf semidetached postcataclysmic nova?, *Astrophys. J.* **175**, L79–L83 (1972).

22. Savonije, G. J., de Kool, M. & van den Heuvel, E. P. J. The minimum orbital period for ultra-compact binaries with helium burning secondaries, *Astr. Astrophys.* **155**, 51–57 (1986).

23. Paczynski, B. Gravitational waves and the evolution of close binaries, *Acta Astron.* **17**, 287–296 (1967).

24. Tout, C. A., Pols, O. R., Eggleton, P. P. & Han, Z. Zero-age main-sequence radii and luminosities as analytic functions of mass and metallicity, *Mon. Not. R. astr. Soc.* **281**, 257–262 (1996).

25. D’Antona, F. in *Evolutionary Processes in Binary Stars* (eds Wijers, R. A. M. J., Davies, M. B. & Tout, C. A.) 287–306 (Kluwer, Dordrecht, 1996).

26. Stella, L., Campana, S., Colpi, M., Mereghetti, S. & Tavani, M. Do quiescent soft X-ray transients contain millisecond radio pulsars?, *Astrophys. J.* **423**, L47–L50 (1994).

27. van Paradijs, J. On the accretion instability in soft X-ray transients, *Astrophys. J.* **464**, L139–L141 (1996).

28. King, A. R., Kolb, U. & Burderi, L. Black hole binaries and X-ray transients, *Astrophys. J.* **464**, L127–L130 (1996).

29. Verbunt, F. & van den Heuvel, E. P. J. in *X-Ray Binaries* (eds Lewin, W. H. G., van Paradijs, J. & van den Heuvel, E. P. J.) 457–494 (Cambridge Univ. Press, Cambridge, 1995).

Acknowledgements. We thank L. Bildsten, V. Kaspi, A. Levine, R. Nelson, R. Remillard, F. Rasio, S. Thorsett, M. van der Klis, and B. Vaughan for useful discussions, and M. Muno for assistance with the data analysis. We also thank F. Marshall, J. Swank and the RXTE team at NASA/Goddard Space Flight Center for arranging these target-of-opportunity observations and the necessary follow-up. This work was supported by NASA.

Correspondence should be addressed to D.C. (e-mail: deepto@space.mit.edu).