Pushing the limit on neutron star spin rates

Duncan Galloway
Centenary Fellow, School of Physics, University of Melbourne, VIC 3010 Australia

Abstract. Millisecond X-ray pulsars consist of a rapidly-spinning neutron star accreting from a low-mass stellar companion, and are the long-sought evolutionary progenitors of millisecond radio pulsars, as well as promising candidate sources for gravitational radiation. The population of these sources has grown significantly over the last three years, with the discovery of six new examples to bring the total sample to seven. Three sources are ultracompact binaries with H-depleted donors and orbital periods of \( \approx 40 \) min, like the 185 Hz pulsar XTE J0929-314. Three more have orbital periods of 2 hr or longer, similar to IGR J00291+5934, first detected in outburst by INTEGRAL in December 2004. The neutron star in this 2.46 hr binary has the most rapid spin of the accreting pulsars at 599 Hz. The most recently-discovered pulsar, HETE J1900.1-2455 (377 Hz), has an intermediate orbital period of 83.3 min, and has been active for more than 1 yr, much longer than the typical transient outburst. Pulsations were detected only in the first few months of the outburst; this source has since resembled a faint, persistent non-pulsing low-mass X-ray binary, typical of the broader low-mass X-ray binary population.

Introduction

Neutron stars accreting from low-mass binary companions (low-mass X-ray binaries, or LMXBs) have orbital periods of typically a few hours, and characteristically exhibit bursts from thermonuclear ignition of accreted material on the surface (e.g. Lewin et al. 1993). These objects are the evolutionary precursors to the “recycled” millisecond radio pulsars, which are thought to have been spun-up by an extended period of accretion. There are > 100 LMXBs known (Liu et al. 2001); most give no observational indications of their (presumably) rapid spin, although since 1996 some have been found to exhibit oscillations in the range 45–620 Hz only during thermonuclear bursts (e.g. Strohmayer & Bildsten 2000). Since the discovery of the 401 Hz pulsar SAX J1808.4–3658 in 1998 (Wijnands & van der Klis 1998), an additional subset of LMXBs has emerged which consistently exhibit pulsations (e.g. Wijnands 2004). Two sources show pulsations and burst oscillations at the same frequency, confirming that the latter phenomenon also traces the neutron-star spin (Chakrabarty et al. 2003). Precisely what is different about these accretion-powered millisecond pulsars (and the burst oscillation sources) that allows us to measure the spin is not clear.

Here I describe the properties of three of the seven accretion-powered millisecond pulsars, the first two representative of the two broad classes of binary which make up this group. Observations were made with the Proportional
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Counter Array (PCA; Jahoda et al. 1996) aboard the Rossi X-ray Timing Explorer (RXTE). The PCA consists of five co-aligned proportional counter units (PCUs), sensitive to photons in the energy range 2–60 keV and with a total effective area of $\approx 6500 \text{ cm}^2$. Arriving photons are time-tagged to approximately $1\mu$s, and their energy is measured to a precision of $<18\%$ at 6 keV. The PCA is presently the only instrument with sufficient sensitivity and temporal resolution to reliably detect the persistent pulsations in the accretion-powered millisecond pulsars.

**XTE J0929$-$314**

This high–Galactic-latitude X-ray transient was first detected in outburst during April 2002 by the All-Sky Monitor (ASM) aboard RXTE (Galloway et al. 2002). The ASM consists of three scanning shadow cameras sensitive to 1.5–12 keV photons which provides 90 s exposures of most of the sky every 96 min. XTE J0929–314 was identified using a “deep sky map” technique, in which maps of flux residuals are constructed by cross-correlating the predicted coded mask pattern against the best-fit data residuals for each 4$'$ cell in the field of view. The resulting sensitivity for new sources is as low as $\approx 15$ mCrab away from the Galactic center, compared to the typical $\approx 50$ mCrab threshold for individual camera snapshots.

PCA observations revealed 185 Hz (5.4 ms) pulsations, with a fractional rms amplitude of 3–7%, modulated by a 43.6 min binary orbit. The Roche lobe in such a tiny binary cannot contain a main-sequence companion, indicating that the mass donor is highly evolved and H-poor (Nelson et al. 1986). The system has one of the smallest measured mass functions ($2.7 \times 10^{-7} M_\odot$) of any stellar binary. The binary parameters imply a $\approx 0.01 M_\odot$ white dwarf donor with a moderately high inclination. XTE J0929–314 was the second ultracompact binary millisecond pulsar discovered, after XTE J1751–305 (42 min; Markwardt et al. 2002) and was later joined by a third, XTE J1807–294 (40 min; Markwardt et al. 2003). It is an open question why the orbital periods of these sources should cluster so closely around 40 min.

XTE J0929–314 remained X-ray active for just over two months, by which time the RXTE observations revealed spin-down at an average rate of $\dot{\nu} = (-9.2 \pm 0.4) \times 10^{-14} \text{ Hz s}^{-1}$. The spin-down torque may arise from magnetic coupling to the accretion disk, a magnetohydrodynamic wind, or gravitational radiation from the rapidly spinning pulsar.

**IGR J00291+5934**

This recurrent X-ray transient was initially identified by ESA’s International Gamma-Ray Astrophysics Laboratory INTEGRAL in 2004 December, during a series of Galactic plane scans conducted every 12 d (Shaw et al. 2005). The source was detected with the IBIS/ISGRI coded-mask imager (Ubertini et al. 2003; Lebrun et al. 2003), which is sensitive to photons in the range 15 keV to 1 MeV and with a $29^\circ \times 29^\circ$ field of view.

The RXTE/PCA observations which followed revealed 599 Hz (1.67 ms) pulsations with a fractional rms amplitude of 9% (3–13 keV). The neutron star
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Figure 1. **Left panel** X-ray flux evolution of IGR J00291+5934 during the 2004–5 outburst and into quiescence. The inferred 0.5–10 keV flux from RXTE observations is plotted as filled circles, while the flux from Chandra observations are plotted as open squares. After Jonker et al. (2005). **Right panel** Spin frequency for rapidly-rotating accreting neutron stars as a function of the binary orbital period. The orbital period is known for 7 of the 13 burst oscillation sources (open squares), but all 7 of the known millisecond pulsars (filled circles). On each axis we also plot the distribution of each parameter separately for the burst oscillation sources (dotted line, including the sources without a detected spin frequency) and pulsars (solid line).

The source remained active for less than 20 d (Fig. 1, left). Chandra observations revealed significant variability in quiescence (Jonker et al. 2005). Once the source position was known, a search of earlier RXTE/ASM observations revealed two prior outbursts, three and six years before. The outburst recurrence time is similar to that of SAX J1808.4−3658 (see also Galloway 2006).

**HETE J1900.1−2455**

The most recently-discovered accretion-powered pulsar, HETE J1900−2455 exhibits distinctly different behaviour in several respects to the rest of the population. The source was discovered in 2005 June when a strong thermonuclear (type-I) burst was detected by HETE-II (Vanderspek et al. 2005). HETE-II was designed to study gamma-ray bursts (Ricker et al. 2003), but thanks to sensitivity extending into the X-ray band can also detect thermonuclear bursts from accreting neutron stars.

Subsequent RXTE observations of the field revealed pulsations at 377.3 Hz (Morgan et al. 2005) as well as Doppler shifts of the apparent pulsar frequency,
originating from orbital motion in the 83.25 min binary \cite{Kaaret2006}. In this case the Roche lobe can accommodate a brown dwarf with no need for extra heating.

The rms amplitude of the pulsations was unusually low compared to the other pulsars, at best 2%. During the initial RXTE observations, the source underwent a short-lived flare after which the pulsations became undetectable. Such behaviour has not been observed in the other six pulsars, in which pulsations are consistently detected while the sources are X-ray bright. However, the pulsar outburst has also lasted much longer than in the other sources \cite{Galloway2005b}, and in fact at the time of writing (2006 June) the source is still active and being monitored with regular RXTE observations. Assuming that activity continues at the present level, the time-averaged accretion rate (at the estimated distance of 5 kpc \cite{Kawai2005}) is the highest amongst all of the millisecond pulsars \cite{Galloway2006}.

**Discussion**

Accretion-powered millisecond pulsars represent a rapidly-growing subclass of LMXBs. The present sample is sufficiently small that new examples can still reveal vital clues as to the physics of these extreme objects; consequently, searches for, and observations of, new examples are a high priority for RXTE and other X-ray missions. Observations of HETE J1900.1−2455 suggest, for the first time, a connection between the transient pulsars and the non-pulsing (typically) persistent LMXB population.

The combined spin distribution for rapidly-rotating neutron stars, including both accretion- and rotation-powered, has a present maximum of 716 Hz \cite{Hessels2006}. This value is substantially below the expected breakup frequency, and while selection effects may explain the non-detection of faster radio pulsars, no such effects reduce the likelihood of detecting faster pulsars in the X-ray band. It has been suggested that the torques which spin-up accreting neutron stars may be balanced at high spin frequencies by gravitational radiation \cite[e.g.][]{Bildsten1998}. A Bayesian analysis suggests that the observed spin frequency distribution of accreting neutron stars is consistent with a uniform distribution up to some maximum value between 700 and 800 Hz \cite{Chakrabarty2003, Chakrabarty2005}. If this “speed limit” is indeed imposed by gravitational wave emission, there is the exciting possibility of detecting these sources with the next generation of gravitational wave detectors, such as the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO; see \cite{Abbott2005}). By virtue of its “quasi-persistent” behaviour, HETE J1900.1−2455 is presently the best accretion-powered millisecond pulsar candidate for the detection of gravitational radiation.

While the observed distribution of spin frequencies does not appear significantly different between the burst oscillation sources and pulsars, the orbital periods are substantially shorter on average (Fig. 1, right), particularly when compared to the entire LMXB population. The K-S test statistic comparing the \( P_{\text{orb}} \) distribution of the millisecond pulsars and the known values for the non-pulsing LMXBs \cite{Liu2001} is 0.751, corresponding to a 99.9% probability that the two populations are not drawn from the same distribution.
The question of why certain sources exhibit persistent pulsations and others do not, remains open. However, more detailed studies of the behaviour of HETE J1900.1–2455 may soon shed light on this question.

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References
Abbott, B. et al. (LIGO Science Collaboration) 2005, Phys.Rev.Lett, 94, 181103
Bildsten, L. 1998, ApJ, 501, L89
Chakrabarty, D. 2005, in Binary Radio Pulsars, ed. F. A. Rasio & I. H. Stairs (San Francisco: ASP Conf. Ser. 328), 279 [astro-ph/0408004]
Chakrabarty, D., Morgan, E. H., Muno, M. P., Galloway, D. K., Wijnands, R., van der Klis, M., & Markwardt, C. B. 2003, Nat, 424, 42
Galloway, D. K. 2006, in The Transient Milky Way: a perspective for MIRAX, ed. F. D’Amico, J. Braga, & R. Rothschild (Melville, NY: AIP; [astro-ph/0604345])
Galloway, D. K., Chakrabarty, D., Morgan, E. H., & Remillard, R. A. 2002, ApJ, 576, L137
Galloway, D. K., Markwardt, C. B., Morgan, E. H., Chakrabarty, D., & Strohmayer, T. E. 2005a, ApJ, 622, L45
Galloway, D. K., Morgan, E. H., Kaaret, P., Chakrabarty, D., & Suzuki, M. 2005b, The Astronomer’s Telegram, 657
Hessels, J. W. T., Ransom, S. M., Stairs, I. H., Freire, P. C. C., Kaspi, V. M., & Camilo, F. 2006, Science, in press [astro-ph/0601337]
Jahoda, K., Swank, J. H., Giles, A. B., Stark, M. J., Strohmayer, T., Zhang, W., & Morgan, E. H. 1996, Proc. SPIE, 2808, 59
Jonker, P. G., Campagna, S., Steeghs, D., Torres, M. A. P., Galloway, D. K., Markwardt, C. B., Chakrabarty, D., & Swank, J. 2005, MNRAS, 361, 511
Kaaret, P., Morgan, E. H., Vanderspek, R., & Tomsick, J. A. 2006, ApJ, 638, 963
Kawai, N., Suzuki, M., & for the HETE Team. 2005, The Astronomer’s Telegram, 534
Lebrun, F. et al. 2003, A&A, 411, L141
Lewin, W. H. G., van Paradijs, J., & Taam, R. E. 1993, Space Sci.Rev., 62, 223
Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2001, A&A, 368, 1021
Markwardt, C. B., Juda, M., & Swank, J. H. 2003, IAU Circ.
Markwardt, C. B., Swank, J. H., Strohmayer, T. E., in ’t Zand, J. J. M., & Marshall, F. E. 2002, ApJ, 575, L21
Morgan, E., Kaaret, P., & Vanderspek, R. 2005, The Astronomer’s Telegram, 523
Nelson, L. A., Rappaport, S. A., & Joss, P. C. 1986, ApJ, 304, 231
Ricker, G. R. et al. 2003, in AIP Conf. Proc. 662: Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission, ed. G. R. Ricker & R. K. Vanderspek, 3–16
Shaw, S. E. et al. 2005, A&A, 432, L13
Strohmayer, T. & Bildsten, L. 2006, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge University Press), [astro-ph/0301544]
Ubertini, P. et al. 2003, A&A, 411, L131
Vanderspek, R., Morgan, E., Crew, G., Graziani, C., & Suzuki, M. 2005, The Astronomer’s Telegram, 516
Wijnands, R. 2004, in Proceedings of the 2nd BeppoSAX Conference: "The Restless High-Energy Universe", Amsterdam, 5–9 May 2003, ed. E. P. J. van den Heuvel, R. A. M. J. Wijers, & J. J. M. in ’t Zand, Vol. 132, 496–505
Wijnands, R. & van der Klis, M. 1998, Nat, 394, 344