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DISCOVERY OF A HIGH-LATITUDE ACCRETING MILLISECOND PULSAR IN AN ULTRACOMPACT BINARY

Duncan K. Galloway, Deepto Chakrabarty[1,2], Edward H. Morgan, and Ronald A. Remillard
Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139;
duncan,deepto,ehm,rr@space.mit.edu
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ABSTRACT

We have identified the third known accretion-powered millisecond pulsar, XTE J0929−314, with the *Rossi X-Ray Timing Explorer*. The source is a faint, high–Galactic-latitude X-ray transient in the Galactic bulge ($d \gtrsim 9$ kpc) that was in outburst during 2002 April–June. The 185 Hz (5.4 ms) pulsation had a fractional rms amplitude of 3–7% and was generally broad and sinusoidal, although occasionally double-peaked. The hard X-ray pulses arrived up to 770 μs earlier than the soft X-ray pulses. The pulsar was spinning down at an average rate of $\dot{\nu} = (-9.2 \pm 0.4) \times 10^{-14}$ 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. The pulsations were modulated by a 43.6 min ultracompact binary orbit, yielding the smallest measured mass function ($2.7 \times 10^{-7} M_\odot$) of any stellar binary. The binary parameters imply a $\simeq 0.01 M_\odot$ white dwarf donor and a moderately high inclination. We note that all three known accreting millisecond pulsars are X-ray transients in very close binaries with extremely low mass transfer rates. This is an important clue to the physics governing whether or not persistent millisecond pulsations are detected in low-mass X-ray binaries.

Subject headings: binaries: close — pulsars: individual (XTE J0929−314) — stars: neutron — stars: low-mass, brown dwarfs — X-rays: binaries

1. INTRODUCTION

Accretion-powered millisecond pulsars, the presumed progenitors of millisecond radio pulsars, have proven surprisingly elusive for 20 years. The first example, the X-ray transient SAX J1808.4−3658 ($P_{\rm spin}$ =401 Hz, $P_{\rm orb}$ =2 hr), was identified as a millisecond pulsar only four years ago (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998). This only deepened the puzzle of why more examples are not known, since SAX J1808.4−3658 is very similar to many of the $\simeq 50$ neutron stars in low-mass X-ray binaries (LMXBs) that are not known pulsars (Psaltis & Chakrabarty 1999). Earlier this year, a second system was detected, the X-ray transient XTE J1751−305 ($P_{\rm spin}$ = 435 Hz, $P_{\rm orb}$ =42.4 min; Markwardt & Swank 2002a, 2002b). We report here on the discovery of a third example, again with a very short binary period.

The faint X-ray transient XTE J0929−314 ($l = 260\overset{\circ}{.}1$, $b = 14\overset{\circ}{.}2$) was discovered by the All Sky Monitor (ASM) on the *Rossi X-Ray Timing Explorer (RXTE)* in 2002 April (Remillard 2002). A brief scanning observation with *RXTE* detected persistent 185 Hz pulsations (Remillard, Swank, & Strohmayer 2002), and further timing revealed a circular, 43.6-min binary orbit (Galloway et al. 2002). The high Galactic latitude makes this source ideal for multiwavelength study. Variable optical (Greenhill et al. 2002; Cacella 2002) and radio (Rupen et al. 2002) counterparts were detected at the X-ray source position measured with the *Chandra X-Ray Observatory* (Juett et al. 2002, in preparation), and C III/N III $\lambda\lambda$4640–4650 and Hα λ6563 emission lines were reported in the optical spectrum (Castro-Tirado et al. 2002). In this Letter, we present a detailed analysis of the *RXTE* observations.

2. OBSERVATIONS

XTE J0929−314 is the faintest new transient discovered by the *RXTE* All-Sky Monitor (ASM; Levine et al. 1996). This 1.5–12 keV instrument consists of three scanning shadow cameras which provide 90 s exposures of most points on the sky every 96 min. XTE J0929−314 was identified as a new X-ray source using a "deep sky map" technique, in which maps of the celestial sphere are constructed for each ASM camera using a cross-correlation algorithm applied to weekly accumulations of data. This allows more sensitive searches for new sources (as low as $\simeq 15$ mCrab away from the Galactic center) compared to the $\simeq 50$ mCrab threshold for X-ray error boxes derived from individual camera snapshots.

After XTE J0929−314 was identified by ASM, we obtained a series of pointed *RXTE* observations of the source during 2002 May 2 – June 24 (MJD 52396–52449). Our analysis is primarily based on data from the *RXTE* Proportional Counter Array (PCA; Jahoda et al. 1996), which consists of five identical gas-filled proportional counter units (PCUs) with a total effective area of ≈ 6000 cm^2 and sensitivity to X-ray photons in the 2.5–60 keV range. For all our PCA observations, the data were collected in GoodXenon mode (in addition to the standard data modes), which records the arrival time (1 μs resolution) and energy (256 channel resolution) of every unrejected photon. We estimated the background flux using

[1] Also Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139.
[2] Alfred P. Sloan Research Fellow.

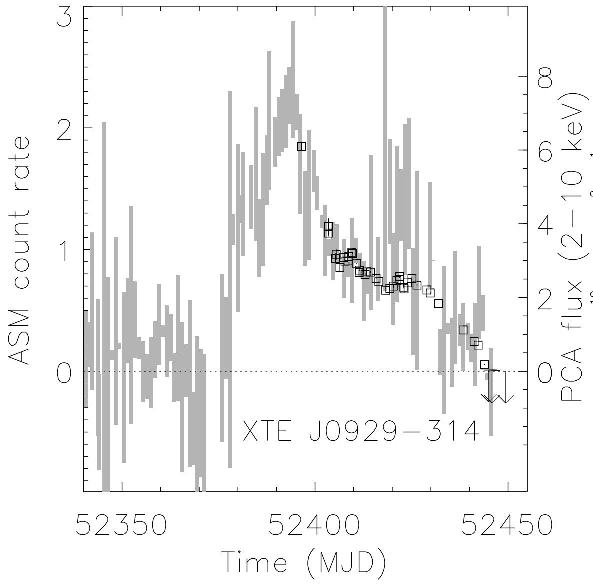

FIG. 1.— 2–10 keV ASM and PCA flux of XTE J0929−314 throughout the 2002 outburst. The 1-d averaged ASM count rate 1σ confidence intervals are shown as shaded regions (left y-axis), while the PCA integrated flux is overplotted as open squares (right hand y-axes). Estimated uncertainties on the PCA flux measurements are also shown, but are typically smaller than the symbol size.

the "CM" faint-source model for PCA gain epoch 5 (from 2000 May 13). The photon arrival times at the spacecraft were converted to barycentric dynamical times (TDB) at the solar system barycenter using the Jet Propulsion Laboratory DE-200 solar system ephemeris (Standish et al. 1992) along with a spacecraft ephemeris and *RXTE* fine clock corrections. The position adopted was that of the optical counterpart (Greenhill et al. 2002). Data from the 20–200 keV High-Energy X-ray Timing Experiment (HEXTE; Gruber et al. 1996) were also used to characterize the hard X-ray spectrum.

3. ANALYSIS AND RESULTS

The ASM and PCA intensity history of XTE J0929−314 is shown in Figure 1. The ASM 1.5–12 keV count rate began rising around MJD 52370 and peaked at $\approx$2.4 count s^{-1} ($\simeq$31 mCrab) on MJD 52394. The initial scanning PCA observation occurred 2 d later, when the decay had already begun. Over the following 20 d the source faded steadily, holding briefly at 10 mCrab on MJD 52420 before declining below the detection limit. The last 3σ PCA detection was on MJD 52443 at a flux of 1.8×10^{-11} erg cm^{-2} s^{-1} (2–10 keV). For subsequent PCA observations, the flux was below the 3σ detection threshold of 7×10^{-12} erg cm^{-2} s^{-1}. The 2–10 keV fluence over the entire outburst was 1.8×10^{-3} erg cm^{-2} s^{-1}. The combined PCA and HEXTE X-ray spectrum was consistent with an absorbed power law+blackbody model, with the following typical model parameters: photon index Γ =1.8–2.0, blackbody temperature kT =0.5–1 keV, and absorption column density $N_{\rm H} < 10^{22}$ cm^{-2}. No X-ray bursts were detected in the data.

For our PCA timing analysis, we selected the 2.8–13 keV (absolute channels 7–30) photon arrival times from the top layer of each PCU and binned them into 2^{-11} s ($\approx$0.5 ms) samples. A 185 Hz pulsed signal was easily detectable in these data. The fractional rms amplitude varied between 3 and 7%. The pulse profile in the initial PCA observation on MJD 52396 contained a weak secondary maximum, but it was broad and single-peaked in all subsequent observations except for the interval MJD 52425–52430, when a second peak was also present. The last 3σ detection of pulsations was on MJD 52442, when the source flux was 7.1×10^{-11} erg cm^{-2} s^{-1} (2–10 keV). A $\simeq$1 Hz quasi-periodic oscillation (FWHM=0.21 Hz) with $\simeq$5% rms amplitude was detected during most of the observations.

We investigated the energy-dependence of the pulse properties by extracting pulse profiles in different energy bands from one of the longer PCA observations on MJD 52408. The rms strength of the pulsation decreased from around 5% at 2–4 keV to 2.5% at 10 keV. Comparison of the pulse phase in each energy band indicated that significant soft lags were present. For each energy band between 2.5 and 10.5 keV the pulse arrival time was earlier than in the adjacent lower energy band, with a cumulative difference of 770 μs. The energy dependence of both the rms strength and the phase lag of the pulsation appeared to flatten above 10 keV; there were insufficient counts to explore the dependence above 20 keV. Similar phase lags were observed in the millisecond pulsations from SAX J1808.4−3658, but that source did not show a similar energy dependence for the pulsed amplitude (Cui, Morgan, & Titarchuk 1998; Ford 2000). We will present a more detailed analysis of the pulse shape variations elsewhere.

The 185 Hz pulsation showed a clear Doppler modulation, and we used a Fourier frequency history to fit a preliminary orbital model (Galloway et al. 2002). We then applied a more precise analysis using the pulse phase techniques commonly employed in radio pulsar timing (see, e.g., Manchester & Taylor 1977). Adopting our preliminary orbital model, we epoch-folded 43.6 min intervals of data (thus averaging over periodic phase residuals caused by errors in our assumed orbital parameters) and used the resulting linear drift in phase residuals to refine our knowledge of the pulsar's spin frequency. Then, we combined this refined spin frequency and the preliminary orbital model to epoch-fold 256 s intervals of data. The resulting phase residuals were used to compute differential corrections to our Keplerian orbit model (see, e.g., Deeter, Boynton, & Pravdo 1981). No significant eccentricity was detectable, but a spin frequency derivative substantially improved the fit. Our best-fit orbit and spin parameters for the pulsar are given in Table 1. The pulse time delays due to the orbit, as well as the effect of the spin frequency derivative are shown in Figure 1. The large residuals in the bottom panel of Figure 2 around MJD 52425 may be due in part to systematic effects caused by pulse shape variations.

4. DISCUSSION

From the presence of persistent millisecond pulsations over a wide luminosity range in XTE J0929−314, we can infer an upper limit on the pulsar's surface dipole magnetic field strength of $B \lesssim 1\times10^9\, d_{\rm 10kpc}$ G from accretion torque theory (Psaltis & Chakrabarty 1999). This is consistent with the expectation that the neutron star is a recycled

TABLE 1
ORBIT AND SPIN PARAMETERS FOR XTE J0929–314

Parameter	Value
Orbital period, $P_{\rm orb}$ (s)	2614.746(3)
Projected semimajor axis, $a_{\rm x} \sin i$ (light-ms)	6.290(9)
Epoch of 90° mean longitude, $T_{\pi/2}$ (MJD/TDB)	52405.49434(1)
Eccentricity, e	< 0.007 (2σ)
Spin frequency, ν_0 (Hz)	185.105254297(9)
Epoch of spin frequency, t_0 (MJD/TDB)	52396.0
Spin frequency derivative, $\dot{\nu}$ (Hz s^{-1})	$-9.2(4) \times 10^{-14}$
χ^2/dof	1506/907

pulsar whose magnetic field has decayed during prolonged mass transfer (Bhattacharya & van den Heuvel 1991). It is interesting to note that the system has binary parameters that are extremely similar to those of the other recently discovered millisecond X-ray pulsar XTE J1751−305 (Markwardt & Swank 2002b) as well as the slow (7.6 s) accreting X-ray pulsar 4U 1626−67 (Middleditch et al. 1981; Schulz et al. 2001), pointing to a similar evolutionary path. A puzzling aspect is that, unlike the two millisecond pulsars, the LMXB 4U 1626−67 has a strong (3×10^{12} G) magnetic field, which may indicate that its neutron star was formed recently through accretion-induced collapse (see Yungelson, Nelemans, & van den Heuvel 2002 and references therein).

We can estimate a crude lower bound on the distance to XTE J0929−314 by first noting that the time-averaged mass transfer rate driven by gravitational radiation in this ultracompact binary is (Faulkner 1971)

$$\dot{M}_{\rm GW} = 7 \times 10^{-12} \left(\frac{M_{\rm x}}{2\,M_\odot}\right)^{2/3} \left(\frac{M_{\rm c}}{0.01\,\odot}\right)^{2} M_\odot\,{\rm yr}^{-1}, \quad (1)$$

where $M_{\rm x}$ and $M_{\rm c}$ are the neutron star and companion masses, respectively. If we assume that the mass accretion rate during the outburst is at least as large as $\dot{M}_{\rm GW}$, then our flux limit at the end of the outburst requires a distance $d \gtrsim 9$ kpc. Also, given a source recurrence time of $\gtrsim 6.5$ yr (the time since *RXTE* was launched), the 2002 outburst fluence implies a mean mass transfer rate equal to $\dot{M}_{\rm GW}$ for $d \gtrsim 9$ kpc. We thus conclude that the source lies in the Galactic bulge. Our limits indicate that the mass accretion rate $\dot{M}$ during the outburst was not more than a few percent of the Eddington critical rate.

The detection of spin-down during the outburst may provide an opportunity to test accretion torque theory for X-ray pulsars in the low-B regime. The torque on a magnetic star from a prograde accretion disk tends to spin-up the star for sufficiently high $\dot{M}$, while accretion will be centrifugally inhibited (the so-called "propeller" regime) for sufficiently low $\dot{M}$. However, for an intermediate range of $\dot{M}$, the positive material torque due to accretion may be dominated by a spin-down torque due to one of a variety of mechanisms, even while accretion persists. Two possible spin-down mechanisms include magnetic coupling of the accretion disk and the magnetosphere (Ghosh & Lamb 1979, 1991) and expulsion of a centrifugally driven magnetohydrodynamic wind (Anzer & Börner 1980; Arons et al. 1984; Lovelace et al. 1995). In either case, the torque should not exceed the characteristic

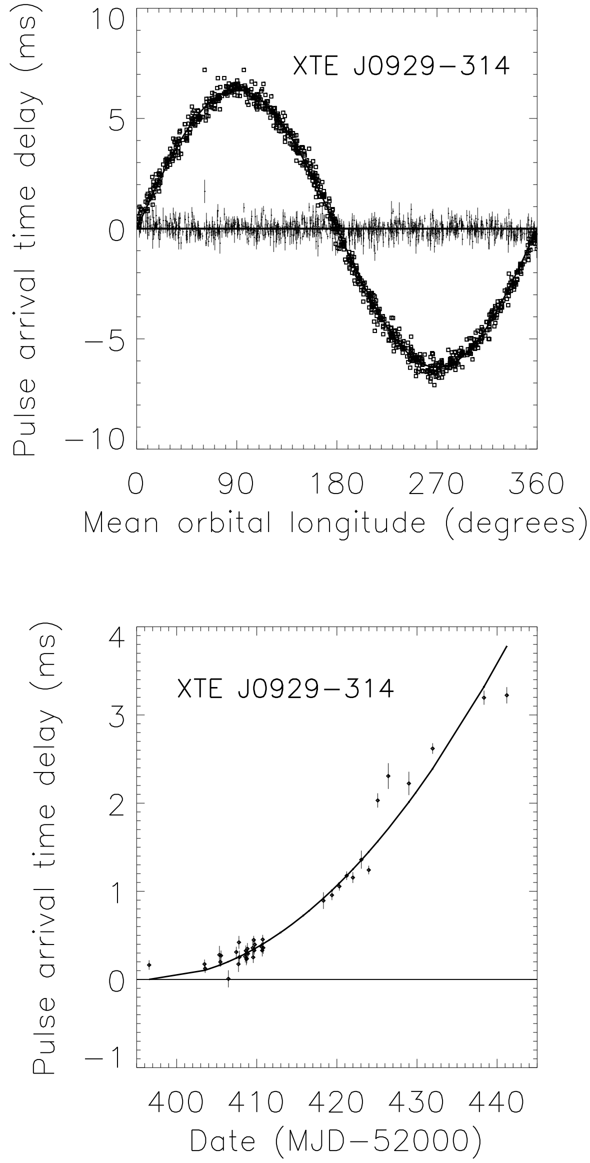

FIG. 2.— Pulse timing residuals in XTE J0929−314. The top panel shows the fit residuals with and without the Keplerian orbit included, while the bottom panel shows the residuals with the $\dot{\nu}$ term excluded. Error bars represent 1σ uncertainties.

accretion torque $\dot{M}\sqrt{GM_{\rm x}r_{\rm co}}$ (where $r_{\rm co}$=50 km is the pulsar's corotation radius), which is consistent with our measured $\dot{\nu}$ for $d \gtrsim 9$ kpc. Another possible mechanism is gravitational radiation by the rapidly spinning pulsar (Bildsten 1998; Andersson, Kokkotas, & Stergioulas 1999; Levin 1999). Some of these issues can be explored by examining the relation between $\dot{M}$ and $\dot{\nu}$, which has been done extensively for high-B neutron stars (e.g., Bildsten et al. 1997) but never for the low-B case. A detailed analysis of the $\dot{M}$-$\dot{\nu}$ correlation will first require a better understanding of the pulse shape variations, in order to limit systematic uncertainties in the frequency history. Such work is currently in progress.

White dwarfs and neutron stars accreting from a hydrogen-rich companion cannot evolve to binary periods below about 80 min, corresponding to the so-called "period minimum" observed for most cataclysmic variables and LMXBs (Paczynski & Sienkiewicz 1981; Rappaport, Joss, & Webbink 1982). Ultracompact ($P_{\rm orb} \lesssim$ 80 min) binaries like XTE J0929−314 must therefore have a low-mass, hydrogen-depleted (and probably degenerate) donor (Nelson, Rappaport, & Joss 1986). Our measured orbital parameters further constrain the nature of the donor in this system. The pulsar mass function, $f_{\rm X} = 2.7 \times 10^{-7}\, M_\odot$, is the smallest presently known for any stellar binary. It gives a minimum companion mass ($i = 90°$) of $M_{\rm c} = 0.008\, M_\odot$ for $M_{\rm x} = 1.4\, M_\odot$; it also implies $M_{\rm c} < 0.03 M_\odot$ (95% confidence) for $M_{\rm x} = 2 M_\odot$ (for a uniform a priori distribution in $\cos i$). The mass-radius relation for a Roche-lobe–filling donor in a 43.6 min binary is $R_{\rm c} = 0.04(M_{\rm c}/0.01\, M_\odot)^{1/3}\, R_\odot$ (Faulkner et al. 1972). As expected, this has no intersection with the theoretical mass-radius relation for very low-mass hydrogen-rich stars (i.e. brown dwarfs, Chabrier et al. 2000; cf. Bildsten & Chakrabarty 2001). However very low-mass white dwarfs composed of either helium (Zapolsky & Salpeter 1969; Nelemans et al. 2001) or carbon (Lai, Abrahams, & Shapiro 1991) are easily consistent for masses of $\simeq 0.01\, M_\odot$, implying that the system has a relatively high (and thus probable) inclination. It may be possible for a helium dwarf donor to retain a small residual hydrogen content (Podsiadlowski, Rappaport, & Pfahl 2002); this is of particular interest, given the report of an Hα λ6563 emission line in the optical spectrum (Castro-Tirado et al. 2002).

Binary evolution theory predicts that many (if not most) of the $\simeq$50 known neutron stars in LMXBs are spinning at millisecond periods (Bhattacharya & van den Heuvel 1991). Of these, only three are now known pulsars, with persistent millisecond pulsations during their X-ray active states.[3] All three are low-luminosity transients in very close binaries, with extremely small time-averaged $\dot{M}$; evidently, millisecond pulsations are easier to detect in such systems. This supports the suggestion that magnetic screening by freshly accreted material may prevent the formation of persistent X-ray pulses in NS/LMXBs with $\dot{M}$ above a critical value (Cumming, Zweibel, & Bildsten 2001).

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[3] Another ten NS/LMXBs show millisecond oscillations during thermonuclear X-ray bursts; these are probably also signatures of rotation (see, e.g., Strohmayer & Markwardt 2002).