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Production and evolution of millisecond X-ray and radio pulsars ☆

Frederick K. Lamb

Center for Theoretical Astrophysics and Departments of Physics and Astronomy, University of Illinois at Urbana-Champaign,
1110 W. Green Street, Urbana, IL 61801-3080, USA

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Abstract

Observations using the *Rossi X-ray Timing Explorer* (*RXTE*) have discovered dozens of accreting neutron stars with millisecond spin periods in low-mass binary star systems. Eighteen are millisecond X-ray pulsars powered by accretion or nuclear burning or both. These stars have magnetic fields strong enough for them to become millisecond rotation-powered (radio) pulsars when accretion ceases. Few, if any, accretion- or rotation-powered pulsars have spin rates higher than 750 Hz. There is strong evidence that the spin-up of some accreting neutron stars is limited by magnetic spin-equilibrium whereas the spin-up of others is halted when accretion ends. Further study will show whether the spin rates of some accretion- or rotation-powered pulsars are or were limited by emission of gravitational radiation.

Keywords: Accretion; Accretion disks; Pulsars; X-rays: binaries; Stars: neutron

1. Observed properties of millisecond X-ray and radio pulsars

In this brief review, a pulsar is considered a millisecond pulsar (MSP) if its spin period P_s is <10 ms (spin frequency $\nu_s > 100$ Hz). Seven accretion-powered and 13 nuclear-powered X-ray MSPs are now known (see Table 1). All are accreting neutron stars in low-mass X-ray binary systems (LMXBs). Two of the accretion-powered MSPs become nuclear-powered MSPs during thermonuclear X-ray bursts. Kilohertz quasi-periodic oscillations (QPOs) have so far been detected in the accretion-powered X-ray emission of more than two dozen neutron stars in LMXBs, with frequencies ranging from ~100 to ~1300 Hz (Lamb, 2003; van der Klis, 2006). They have been seen in 8 of the 13 known nuclear-powered MSPs and 2 of the 7 known accretion-powered MSPs (see Table 1).

The discovery of a pair of kilohertz QPOs in the 401 Hz accretion- and nuclear-powered X-ray pulsar SAX J1808.4−3658 (Chakrabarty et al., 2003; Wijnands et al., 2003), of a pair of kilohertz QPOs in the 191 Hz accretion-powered X-ray pulsar XTE J1807.4−294 (Linares et al., 2005), and of burst oscillations in the 314 Hz accretion-powered X-ray pulsar XTE J1814−338 (Strohmayer et al., 2003) has confirmed the relationship between these three distinct types of high-frequency X-ray oscillations.

Except during the first few seconds of some bursts, the nuclear-powered oscillations of SAX J1808 and XTE J1814 have the same frequency and phase as the accretion-powered oscillations. These observations establish beyond any doubt that (1) the nuclear- and accretion-powered oscillations are both produced by spin modulation of the X-ray flux from the stellar surface and (2) the magnetic fields of these stars are strong enough to channel the accretion flow and enforce corotation of gas heated by nuclear burning, which requires fields $\gtrsim 10^7$ G (Miller et al., 1998; Lamb and Yu, 2005). Conversely, the nearly sinusoidal waveforms and low amplitudes of these oscillations indicate that the surface magnetic fields of these neutron stars are less than $\sim 10^{10}$ G (Psaltis and Chakrabarty, 1999). These results confirm that the frequencies of both the accretion- and the nuclear-powered X-ray oscillations are the spin frequencies of these neutron stars.

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E-mail address: fkl@uiuc.edu

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Table 1
Nuclear- and accretion-powered millisecond X-ray pulsars

ν_{spin}	(Hz)[a]	Object	References
619	NK	4U 1608–52	Hartman et al. (2003)
601	NK	SAX J1750.8–2900	Kaaret et al. (2002)
598	A	IGR J00291 + 5934	Markwardt et al. (2004)
589	N	X 1743–29	Strohmayer et al. (1997)
581	NK	4U 1636–53	Zhang et al. (1996); Strohmayer et al. (1998)
567	N	X 1658–298	Wijnands et al. (2001)
549	NK	Aql X-1	Zhang et al. (1998)
524	NK	KS 1731–260	Smith et al. (1997)
435	A	XTE J1751–305	Markwardt et al. (2002)
410	N	SAX J1748.9–2021	Kaaret et al. (2003)
401	ANK	SAX J1808.4–3658	Chakrabarty and Morgan (1998) Wijnands and van der Klis (1998) Chakrabarty et al. (2003) Wijnands et al. (2003)
377	A	HETE J1900.12455	Morgan et al. (2005)
363	NK	4U 1728–34	Strohmayer et al. (1996)
330	NK	4U 1702–429	Markwardt et al. (1999)
314	AN	XTE J1814–338	Strohmayer et al. (2003)
270	N	4U 1916–05	Galloway et al. (2001)
191	AK	XTE J1807.4–294	Linares et al. (2005)
185	A	XTE J0929–314	Galloway et al. (2002)
45	N	EXO 0748–676	Villarreal and Strohmayer (2004)

[a] Spin frequency inferred from periodic or nearly periodic X-ray oscillations. A, accretion-powered millisecond pulsar; N, nuclear-powered millisecond pulsar; K, kilohertz QPO source. See text for details.

None of the 18 currently known accretion- and nuclear-powered X-ray pulsars have spin frequencies higher than 619 Hz (see Table 1). There is no known observational bias against detecting such pulsars. This indicates that few, if any, such pulsars have spin frequencies higher than 750 Hz (Chakrabarty et al., 2003; M.C. Miller, 2005, personal communication). Although too few such pulsars have been observed to establish their spin distribution accurately, the spins of the known MSPs nevertheless provide valuable information about their production and evolution, as discussed below.

A weak-field accreting neutron star typically produces a pair of strong kilohertz QPOs, with frequencies that vary by as much as a factor of five as the star's X-ray flux varies by a factor of two or three (see Miller et al., 1998; Lamb, 2003, 2005; Lamb and Miller, 2006; van der Klis, 2006). As the frequencies of the two kilohertz QPOs vary by hundreds of Hertz, their separation $\Delta\nu_{\mathrm{QPO}}$ remains roughly constant. All the kilohertz QPO pairs detected in X-ray pulsars have $\Delta\nu_{\mathrm{QPO}}$ approximately (sometimes very accurately) equal to either ν_{s} or $0.5\ \nu_{\mathrm{s}}$. For example, the kilohertz QPO pair discovered in XTE J1807.4 has $\Delta\nu_{\mathrm{QPO}} = \nu_{\mathrm{s}}$ (Linares et al., 2005) whereas that discovered in SAX J1808.4 has $\Delta\nu_{\mathrm{QPO}} = 0.5\ \nu_{\mathrm{s}}$ (Wijnands et al., 2003). These findings show that the spin of the star plays a central role in generating its kilohertz QPO pair. This is possible only if the neutron stars that produce kilohertz QPOs have magnetic fields $\gtrsim 10^8$ G (Miller et al., 1998; Lamb and Miller, 2001, 2006). The central role played by the star's spin frequency means that information about its spin frequency can be extracted from the frequencies of its kilohertz QPOs, even if accretion- or nuclear-powered oscillations have not yet been detected.

Altogether, more than two dozen accreting neutron stars have spin rates and magnetic fields high enough for them to become rotation-powered radio-emitting MSPs when accretion ceases, supporting the hypothesis (Alpar et al., 1982; Radhakrishnan and Srinivasan, 1982) that such neutron stars are the progenitors of the radio MSPs. Many new rotation-powered radio MSPs have been discovered in recent years and dozens are now known (see Lorimer, 2005). Eighty binary and millisecond radio pulsars have been associated with the Galactic disk. More than one hundred radio pulsars have been discovered in 24 globular clusters in the Galaxy (Lorimer, 2005). In November 2005, a radio pulsar was discovered in Terzan 5 with a spin frequency of 716 Hz (Hessels et al., 2006), higher than the 642 Hz spin frequency of the first radio MSP discovered (Backer et al., 1982).

2. Production of millisecond X-ray and radio pulsars

Production and spin evolution of accretion-powered millisecond X-ray pulsars. The timescale on which accretion from a disk doubles the spin rate of a slowly rotating magnetic neutron star is (Ghosh and Lamb, 1979b, 1992)

$$t_{\mathrm{s}} \equiv 2\pi\nu_{\mathrm{s}} I/[\dot{M}(GMr_{\mathrm{m}})^{1/2}]$$

$$\sim 10^8\,\mathrm{years}\left(\frac{\nu_{\mathrm{s}}}{300\ \mathrm{Hz}}\right)\left(\frac{\dot{M}}{0.01\dot{M}_E}\right)^{-1+\alpha/3}. \qquad (1)$$

Here, ν_{s}, M, and I are the star's spin frequency, mass, and moment of inertia, $\dot{M}$ is the mass accretion rate onto the