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Accretion-powered millisecond pulsars

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Abstract

I review X-ray observations of accretion-powered millisecond pulsars and current theories for formation of their spectra and pulse profiles.

Keywords: Accretion; Accretion discs; Stars, Neutron; X-rays, Binaries

1. Introduction

A number of rapidly spinning neutron stars in low-mass X-ray binaries were discovered with the *Rossi X-ray Timing Explorer* (*RXTE*) in the recent years. These discoveries confirm the ideas on the formation of radio (recycled) millisecond pulsars in low-mass X-ray binaries (see review by Bhattacharya, 1995). Accretion of matter onto a neutron star results in an increase in its spin rate to millisecond periods, if the magnetic field of the star is below about 10^9 G.

Thirteen sources show nearly coherent oscillations for a few seconds during X-ray bursts at frequencies ranging from 270 to 619 Hz (see Strohmayer and Bildsten, 2006 for a review). These are now called nuclear-powered millisecond pulsars. The number of accretion-powered millisecond pulsar (AMSP) showing pulsations in the persistent emission reached seven by June 2005. A more observationally inclined review of AMSP is given by Wijnands (2005). Here, I concentrate on the results of the X-ray spectroscopy, analysis of pulse profiles, and our present theoretical understanding.

2. Pulsars parameters

The first real AMSP SAX J1808.4−3658 was discovered in 1998 by Wijnands and van der Klis (1998). Now (September 2005) there are seven AMSPs with spin frequencies from 185 up to 599 Hz (see Table 1). The fastest AMSP, IGR J00291 + 5934 with the period of just 1.67 ms is the fifth fastest among all known pulsars (including radio- and nuclear-powered MSPs). The last AMSP HETE J1900.1−2455 was discovered in June 2005.

AMSPs show pulse frequency variations. These observations are very important for understanding of the evolution of the neutron stars in low-mass X-ray binaries towards radio MSPs. They would also shed some light on a complicated problem of the interaction of the magnetosphere with the accretion flow. One expects a spin-up rate

$$\dot{\nu} = 3.7\times10^{-13} \times \frac{L_{37}}{\eta_{-1} I_{45}} \left(\frac{R_{\rm m}}{R_{\rm co}}\right)^{1/2} \left(\frac{M}{1.4{\rm M}_\odot}\right)^{2/3} \left(\frac{\nu_{\rm spin}}{600}\right)^{-1/3} {\rm Hz\ s^{-1}},$$

where (notation $Q = 10^x\ Q_x$ in cgs units is used) I is the neutron star moment of inertia, L is the luminosity, η is the accretion efficiency, $R_{\rm m}$ and $R_{\rm co}$ are the magnetospheric and corotation radii. Some reported $\dot{\nu}$ are, however, *negative* implying pulsar slowing down during the outburst (Galloway et al., 2002; Morgan et al., 2003). Markwardt (2004) finds wild swings in the apparent spin frequency of both signs resulting in the total fractional phase shift less than 0.15. These could be, however, artifacts of the pulse profile variations (see Section 4). The reported positive $\dot{\nu} \sim 8\times10^{-13}$ Hz/s for IGR J00291 + 5934 (Falanga et al., 2005b) is larger than expected by a factor of 5 (since

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Table 1
Parameters of the accretion-powered millisecond pulsars

	Source	P_{orb}[a] (min)	ν_{spin}[b] (Hz)	$a_x \sin i$[c] (lt-ms)	f_x[d] ($M_\odot$)	$M_{\mathrm{c,min}}$[e] ($M_\odot$)
1	SAX J1808.4−3658	121	401	62.809	3.779×10^{-5}	0.043
2	XTE J1751−305	42.4	435	10.113	1.278×10^{-6}	0.014
3	XTE J0929−314	43.6	185	6.290	2.9×10^{-7}	0.0083
4	XTE J1807−294	40.1	191	4.75	1.49×10^{-7}	0.0066
5	XTE J1814−338	257	314	390.3	2.016×10^{-3}	0.17
6	IGR J00291+5934	147	599	64.993	2.813×10^{-5}	0.039
7	HETE J1900.1−2455	83.3	377	18.39	2.00×10^{-6}	0.016

References: [1] Wijnands and van der Klis (1998); Chakrabarty and Morgan (1998); [2] Markwardt and Swank (2002); Markwardt et al. (2002); [3] Remillard et al. (2002); Galloway et al. (2002); [4] Markwardt et al. (2003a); Kirsch et al. (2004); Falanga et al. (2005a); [5] Markwardt and Swank (2003); Markwardt et al. (2003b); [6] Eckert et al. (2004); Markwardt et al. (2004a,b); Galloway et al. (2005); [7] Vanderspek et al. (2005); Morgan et al. (2005); Kaaret et al. (2005).

[a] Orbital period.

[b] Neutron star spin frequency.

[c] Projected semimajor axis.

[d] Pulsar mass function.

[e] Minimum companion mass for a $M_x = 1.4\ M_\odot$ neutron star.

$L_{37} \sim 0.37$). A positional error of $\sim 0''.7$ could result in such a large derivative, while the radio position is known with a $0''.1$ accuracy (Rupen et al., 2004). The motion of the radio source itself does not produce an error larger than $\sim 0''.3$ (for the distance of 5 kpc) a week after the outburst, confirming the reality of the pulsar spin-up and possibly implying a small moment of inertia I.

Accretion-powered pulsars reside in very compact binary systems with orbital periods ranging from 40 min to 4.3 h. Surprisingly three out of 7 pulsars have 42 ± 2 min orbits. Adding to this set also 4U1626-67, 4U1916-05, and X1832-330 (in globular cluster NGC 6652) with orbital periods of 42, 50, and 44 min, respectively, it becomes clear that this interesting fact deserves some explanation (see Nelson and Rappaport, 2003, for a possible scenario). The pulsar mass function

$$f_x = (M_{\mathrm{c}} \sin i)^3/(M_{\mathrm{c}} + M_x)^2 = 4\pi^2 (a_x \sin i)^3/GP^2_{\mathrm{orb}}$$

is very low for all these objects, implying extremely low companion masses consistent with degenerate white (helium or carbon–oxygen) or brown dwarfs (Bildsten and Chakrabarty, 2001; Markwardt et al., 2002; Galloway et al., 2002; Falanga et al., 2005a; Galloway et al., 2005) except XTE J1814−338 which contains probably a hydrogen-rich star (Krauss et al., 2005). All AMSPs are transients with the outbursts repeating every few years and lasting a few weeks. They have a rather low time-average accretion rate of $\sim 10^{-11}\ M_\odot$/yr, which could be the main reason why the magnetic field is still strong enough for pulsations to be observed (Cumming et al., 2001).

3. Broad-band X-ray spectra

The broad-band coverage of the *RXTE* together with *XMM* gave a possibility for studying the spectra of AMSP in great detail. The spectra can be modelled by three components: two soft, thermal looking ones below a few keV and a power-law like tail (see Fig. 1).

The two soft components which can be modelled as thermal emission from a colder ($kT \sim 0.4$–0.6 keV) accretion disc and a hotter ($\sim$1 keV) spot on the neutron star surface. The softer components in XTE J1751−305 and XTE J1807−294 are studied with *XMM* by Gierliński and Poutanen (2005); Falanga et al. (2005a). The inferred inner disk radius $R_{\mathrm{in}} \sim (10\text{–}15)\mathrm{km}/\sqrt{\cos i}$ is consistent with the flow disrupted by the neutron star magnetosphere within a couple of stellar radii. The hotter black body normalization corresponding to the area of $\sim$30–100 km^2 and its pulsation are consistent with it being produced in a spot at the neutron star surface.

A power-law tail (having spectral photon index $\Gamma \sim 1.8 - 2.1$) shows a cutoff around 100 keV and can be fitted with thermal Comptonization. The electron temperature of the Comptonizing medium is around $kT_{\mathrm{e}} \sim 20$–60 keV and Thomson optical depth of $\tau_{\mathrm{T}} \sim 0.7$–2.5 (for a plane-parallel slab geometry) (Gierliński et al., 2002; Poutanen and Gierliński, 2003; Gierliński and Poutanen, 2005; Falanga et al., 2005a). Weakness of the Compton reflection from the disk indicates that the solid angle covered by the disk as viewed from the main emission source (accretion shock) is small, being consistent with $R_{\mathrm{in}} \sim 40$ km (Gierliński and Poutanen, 2005).

The broad-band X-ray spectra of AMSPs are very similar to each other. They also show very little variability during the outbursts (see e.g., Gilfanov et al., 1998; Gierliński and Poutanen, 2005; Falanga et al., 2005b). When fitting spectra with thermal Comptonization models, one also finds that the product of the electron temperature and optical depth is almost invariant (e.g. $[kT_{\mathrm{e}}, \tau_{\mathrm{T}}] = [60$ keV,0.88] in SAX J1808.4−3658; [33 keV,1.7] in XTE J1751−305, [37 keV,1.7] in XTE J1807−294, [49 keV,1.12] in IGR J00291+5934; see Gierliński and Poutanen, 2005; Falanga et al., 2005a,b). The constancy of the spectral slope can be