The Superslow Pulsation X-ray Pulsars in High Mass X-ray Binaries

Wei Wang[*]

National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
E-mail: wangwei@bao.ac.cn

There exists a special class of X-ray pulsars with a very slow pulsation with $P_{\rm spin} >> 1000$ s in the high mass X-ray binaries (HMXBs). Presently two superslow pulsation X-ray pulsars are discovered, 4U 2206+54 with $P_{\rm spin} \sim 5560$ s and 2S 01114+65 with $P_{\rm spin} \sim 9600$ s. Long-term monitoring observations find spin period evolution of two sources: spin-down trend for 4U 2206+54 ($\dot{P}_{\rm spin} \sim 4.9 \times 10^{-7}$ s s^{-1}) and long-term spin-up trend for 2S 0114+65 ($\dot{P}_{\rm spin} \sim -1 \times 10^{-6}$ s s^{-1}) in the last 20 years. Additionally, spectral properties of two superslow pulsation X-ray pulsars show the similar behaviours in X-rays: lower hydrogen column density and harder spectrum at the flux maximum. This characteristics suggested that both two objects belong to the highly obscured binary systems similar to some other supergiant X-ray binaries. The hard X-ray tails above 70 keV are discovered in 2S 0114+65 implying the possible accretion processes similar to a black hole system with the existence of possible hot corona or transient jet. The cyclotron absorption lines at ~ 30 keV and 60 keV in the spectrum of 4U 2206+54 suggest a magnetized neutron star with $B \sim 3 \times 10^{12}$ G. The physical origin of the superslow spin period is still unclear. The possible origin and evolution channel of the superslow pulsation X-ray pulsars are briefly discussed. We suggested that the superslow pulsation X-ray pulsars should be the young neutron star accreting binaries.

[*]Speaker.

1. Introduction

Spin period of neutron stars in the Universe is observed in a wider range in various systems: 1.3 ms – 10 s for radio pulsars; 2 –12 s for magnetars; 1.5 – 30 ms for millisecond pulsars in low mass X-ray binaries; 0.1 – ~ 1000 s for Be X-ray transients; 10 –~ 1000 s for supergiant X-ray binaries. There still exist the neutron star systems with a much longer spin period. Two possible superslow X-ray pulsar candidates were reported recently: 1E 161348-5055 in a young supernova remnant RCW 103 ($P_{spin} \sim 6.67$ hr [6]), and a wind-accretion symbiotic low mass X-ray binary 4U 1954+319 ($P_{spin} \sim 5$ hr [16]). But the observed modulations possibly due to an orbital period cannot be excluded. The other two superslow X-ray pulsars are discovered in HMXBs: 4U 2206+54 with $P_{spin} \sim 5560$ s [19, 22, 23] and an orbital period of 19.12 days [4, 22]; 2S 0114+65 with $P_{spin} \sim 9600$ s [8, 24] and an orbital period of 11.59 days [5].

Two superslow X-ray pulsars are powered by the direct wind-fed accretion from the stellar winds of the companion stars. But they have different types of the companions. The optical counterpart of 4U 2206+54 at a distance of ~ 2.6 kpc was identified as an O9.5V star with a high He abundance[2]. For 2S 0114+65, a type B1a supergiant optical counterpart (LS I+65010) at a distance of ~ 7.2 kpc was identified [18].

In this paper, we will probe the spin period evolution of two superslow pulsation pulsars, and spectral properties, specially orbital phase-resolved spectra of two sources with INTEGRAL long-term monitoring observations. These studies will help us to understand the physical origin and evolution of this peculiar class of neutron star binaries.

2. Spin period variations of superslow pulsation X-ray pulsars

2.1 4U 2206+54

The spin period of the neutron star in 4U 2206+54 was discovered in 2009 [19, 22]. Reig et al. [19] found the spin period of 5559±3 s around MJD 54240 using RXTE/PCA data; and obtained a spin period of 5525±30 s using EXOSAT observations around 1984. Wang [22, 23] found a spin period of $\sim 5550 \pm 50$ around MJD 53719 using INTEGRAL/IBIS data. Finger et al.[9] obtained a spin period of 5554±9 s at MJD 54237 using the Suzaku data; and they also found a spin-period of 5420±28 s around MJD 51141 by re-analyzing the BeppoSAX data, suggesting a spin-down of neutron star in 4U 2206+54 with a spin-down rate of $\sim (5.0 \pm 1.3) \times 10^{-7}$ s s^{-1} when they compared the results by Suzaku and BeppoSAX. With the long-term INTEGRAL observations, we[25] determined the spin period at 5559.3±1.9 s in MJD 54087 and 5566.7±7.0 s in MJD 54258 deriving a spin-down rate of $(4.9 \pm 3.2) \times 10^{-7}$ s s^{-1} from MJD 54080 – 54260[25].

2.2 2S 0114+65

The X-ray source 2S 0114+65 consists of an wind-fed accretion neutron star with its pulse period first measured at ~ 2.78 hr[10]. Hall et al.[11] derived a period of ~ 2.73 hr, and found a spin-up rate of $\sim 6.2 \times 10^{-7}$ s s^{-1} for the neutron star in 2S 0114+65 over ~ 11 yr. Bonning & Falanga[3] obtained a spin period of ~ 2.67 hr, and a spin-up rate of $\sim 8.9 \times 10^{-7}$ s s^{-1} from 1996 to 2004. Farrell et al.[8] analyzed RXTE data around early 2006 to derive a spin period of ~ 2.65 hr. With the INTEGRAL long-term monitoring observations, Wang[24] found a pulse
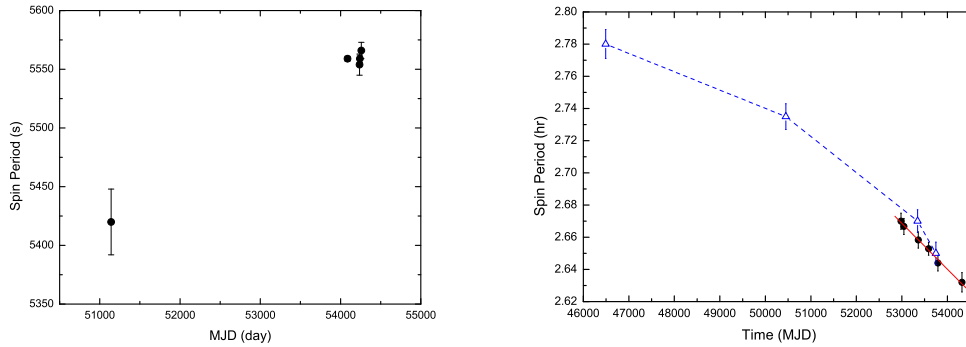
Figure 1: Spin evolution history of 4U 2206+54 (left) and 2S 0114+65 (right) from different observations.

period evolution of ~ 2.67 hour to 2.63 hour from 2003 – 2008 and derived a spin-up rate of 1.09×10^{-6} s s^{-1}. Compared with the previous reported spin-up rate, the spin-up rate of the neutron star in 2S 0114+65 is accelerating (see Fig. 1).

3. Spectral properties of superslow pulsation X-ray pulsars

Both superslow pulsation X-ray pulsars are highly variable X-ray sources, with a luminosity range of $10^{34} - 10^{36}$ erg s^{-1}. We present the orbital phase-resolved spectral properties for 4U 2206+54 and 2S 0114+65 in Figs. 2 & 3 respectively. The spectra are fitted with the absorbed power-law model plus high energy cut-off. The spectral variations in both two sources show a common property. There exist anti-correlations between the flux and hydrogen column density/photon index, i.e., a lower column density and harder spectrum around maximum of X-ray flux. Orbital phase modulation of the hydrogen column density has been also detected in other high mass X-ray binaries like Vela X-1 [12] and EXO 1722-363 [20]. These spectral behaviour over the orbital phase suggested that they should belong to highly obscured X-ray binary systems.

We also search for the possible cyclotron line features in hard X-ray spectra in two systems. The cyclotron absorption lines at ~ 30 keV and 60 keV[1] are detected in 4U 2206+54 (Fig. 4, see [22, 25]), suggesting a magnetized neutron star with the magnetic field of $\sim 3 \times 10^{12}$ G located in the binary. Interestingly, we find that the cyclotron line features of 4U 2206+54 are only detected in a small part (25%) of the whole orbital phase (just before the peak flux)[25]. Unfortunately, we have not find evidence for the magnetic neutron star in 2S 0114+65 with different observations.

In addition, a high energy tail was discovered in the X-ray spectrum of 2S 0114+65 [7, 24]. With detailed studies using INTEGRAL data, we find that high column density may lead to the disappearance of the hard X-ray tails in the spectra[24]: when the derived values of column density are higher than $\sim 3 \times 10^{22}$ cm^{-2}, no hard X-ray tails are detected. How to produce the hard X-ray tails above 70 keV for accreting neutron star in high mass X-ray binaries especially in the wind-fed accretion systems is unclear. It is possible that hot corona exists near neutron stars for wind-fed

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[1]Some residuals in the INTEGRAL data around 60 keV may be expected due to calibration and background uncertainties. This absorption feature need further observations by other missions.
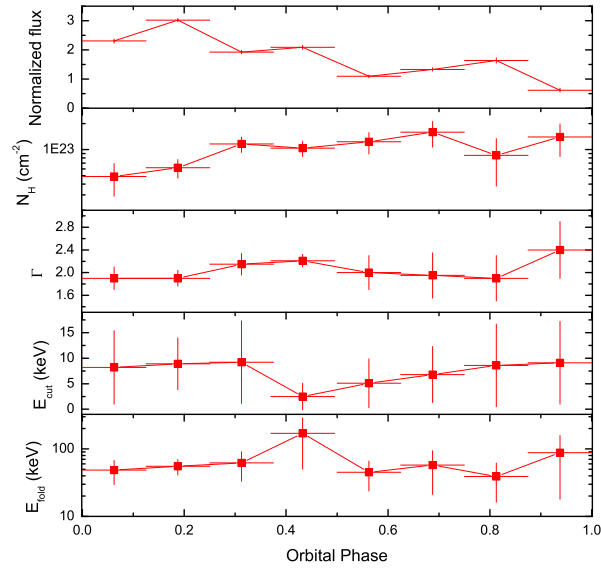
Figure 2: Spectral property variations [25] of 4U 2206+54 with orbital phases.
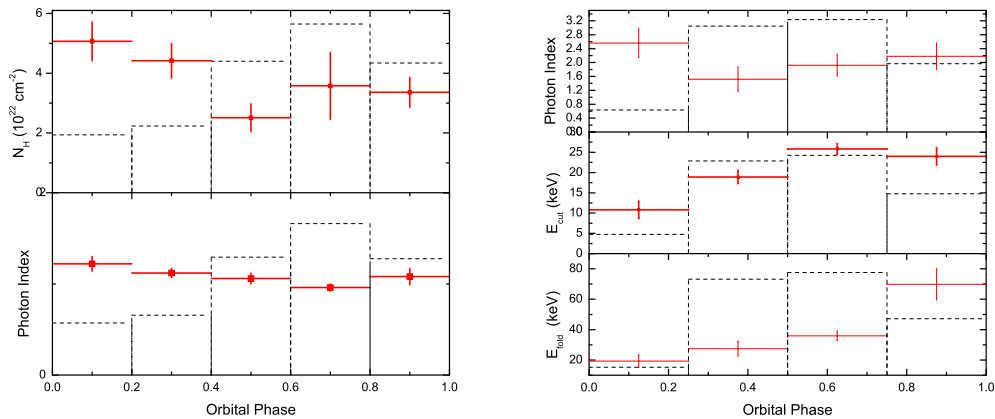

Figure 3: Spectral property variations of 2S 0114+65 with orbital phases (left from RTXE [8]; right from INTEGRAL [24]). The dashed lines show the normalized flux variations.

accretion systems like 2S 014+65; and the dense accretion materials or strong winds prevent the formation of hot corona or depress the comptonization effects.

4. Possible origin and evolution channels of superslow pulsation X-ray pulsars

The spin period evolution of the new-born neutron star generally undergoes three states [1]: *ejector state* in which neutron star spins down through the conventional spin-powered pulsar energy-loss mechanisms; *propeller state* in which spin period decreases by means of interaction between the neutron star magnetosphere and stellar wind of the companion; *accretor state* in which spin
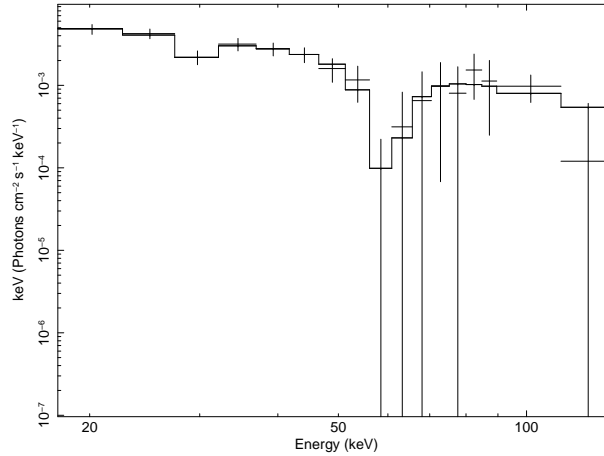
Figure 4: The X-ray spectrum of 4U 2206+54 with two cyclotron absorption lines at $\sim$ 30 keV and 60 keV[22].

period of neutron star reaches a critical value, and the neutron star begins to accrete materials on to the surface, then switches on as the X-ray pulsar. The critical period is defined by equating the corotational radius of the neutron star to the magnetospheric radius, which induces the longest period of several hundred seconds but less than $\sim$ 1000 s for the neutron star of magnetic field $B < B_{cr} = 4.4 \times 10^{13}$ G. Then what is the formation channel for the superlong spin period $>> 1000$ s in this evolutional track?

Li & van den Heuvel [15] have suggested that neutron star spins down to the spin period range longer than 1000 s if the neutron star was born as a magnetar with an initial magnetic field $\geq 10^{14}$ G. This ultra-strong magnetic field could decay to the normal value ranges of $10^{12} - 10^{13}$ G within a few million years, so that 4U 2206+54 and 2S 0114+65 may be defined as magnetar descendants. The alternative suggestion[13] shows that an additional evolution phase *subsonic propeller* state between the transition from *supersonic propeller* state to *accretor* state could allow the spin period increases up to several thousand seconds without the assumption of magnetars. The superslow pulsation neutron star could be formed by the quasi-spherical accretion in wind-fed accreting systems, which is applied to magnetized neutron stars in symbiotic X-ray binaries [17]. Finger et al. [9] interpreted that the neutron star in 4U 2206+54 should be a magnetar with a magnetic field of $\sim (3-5) \times 10^{15}$ G. As we know, magnetar activity would emit X-rays with a typical luminosity of $\sim 10^{35} - 10^{36}$ erg s^{-1} and a typical power-law spectrum in hard X-ray bands (10 $-$ 100 keV) of photon index $\Gamma \sim 1 - 1.5$ for known magnetar candidates [14, 21], which is inconsistent with the observed properties of 4U 2206+54. Magnetar assumption must make present magnetar X-ray luminosity lower than 10^{34} erg s^{-1} for the case of 4U 2206+54. It is still quite interesting that the discovery of the cyclotron absorption line feature around 30 keV would suggest a magnetic field of 3×10^{12} G for the electron cyclotron absorption case, but a magnetic field of $\sim 5 \times 10^{15}$ G for the proton cyclotron line assumption. Thus, difficulty and uncertainties in explaining the long spin period still exist. It is possible that the X-ray pulsar in 4U 2206+54 may not follow the present standard evolution models in close binaries.

Finally, a possible evolution track for the slow-pulsation neutron stars in wind-fed accreting binaries is suggested. There may exist the physical link among slow-pulsation X-ray pulsars: 4U

2206+54 and 2S 0114+65 are the younger systems undergoing rapid spin period evolutions, from rapid spin-down of 4U 2206+54 to rapid spin-up of 2S 0114+65; other supergiant X-ray binaries, like Vela X-1 and EXO 1722-363 are the older systems in the equilibrium spin period range after the rapid evolution phase. In the equilibrium, accreting X-ray pulsars in wind-fed systems would not undergo long-term spin-up/down trends, but the torque changes and fluctuations occur during accretion. This evolution track assumption requires further long-term observations: the spin-up/down process continues in a longer time scale or there exist torque changes in future. These important issues will help us to well understand the origin and evolution of superslow pulsation neutron star systems, and provide new information on the evolution channels of accreting neutron star high mass X-ray binaries.

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