A Peculiar Hard X-ray Flare in Massive X-ray Binary 4U 2206+54

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Abstract: We reported the discovery of a peculiar hard X-ray flare in a massive X-ray binary 4U 2206+54 occurring on 15 December 2005 with a duration of about 2 days. The X-ray flare had a double-main-peak feature. The first peak showed a fast rise and long time decaying light curve about 15 hours with a peak luminosity of 4×10^{36} erg/ s and a hard spectrum (only seen above 5 keV). The second peak had the mean hard X-ray luminosity of 1.2×10^{36} erg/s from 20 – 100 keV with a modulation period at 5550 s which is the pulse period of the neutron star in 4U 2206+54. The hard X-ray flare emit gamma-ray photons above 300 keV with a total released energy higher than 10^{41} erg. The hard X-ray spectrum just before the flare showed cyclotron absorption features at 30 keV and 60 keV, implying a neutron star with magnetic field of 3×10^{12} G. The flare may relate to astrophysical processes around the highly magnetized neutron star. We suggest that the hard X-ray flare could be induced by suddenly enhanced accreting dense materials from stellar winds hitting the polar cap region of the neutron star. This hard X-ray outburst may be a link to supergiant fast X-ray transients though 4U 2206+54 has a different type of companion. The possible formation mechanisms of these long pulsation period X-ray pulsars are also discussed.

Keywords: stars: neutron — X-rays: binaries — X-rays: bursts

1 Introduction

High mass X-ray binaries (HMXB) are X-ray sources composed of an early-type massive star and an accretion compact object (neutron star or black hole). A major part of HMXBs harbor X-ray pulsars believed to be the magnetic neutron stars with a relatively strong magnetic field of $\sim 10^{12}$ G [1]. Their X-ray emission can be powered by the accretion disk (disk-fed) or direct accretion from radiative wind (wind-fed) of the donor star. The high energy luminosity variation is generally due to the change of the orbital phase.

Massive X-ray binary 4U 2206+54 was discovered by the Uhuru satellite [8]. The optical counterpart was identified as an O9.5V star with a high He abundance [3]. Without a circumstellar disk around the donor, the material for accretion and production of high energy emission must come from stellar wind [16]. The wind terminal velocity of 4U2206+54 has a low value of ~ 350 km s^{-1} [19], so using the Bondi-Hoyle formalism wind-fed accretion could produce X-ray luminosity and variability ($L_x \sim 10^{33} - 10^{35}$ erg s^{-1}). 4U 2206+54 is the only permanent wind-fed HMXB with a main-sequence donor though the compact object of unknown nature [19]. X-ray monitoring of 4U 2206+54 by RXTE and SWFIT suggested a modulation period of 19.2 days [6, 23] which is an orbital period.

The nature of the compact object in 4U 2206+54 has been in dispute for a long time. In this work, we report a super-long duration hard X-ray flare in 4U 2206+54 discovered by INTEGRAL/IBIS and RXTE/ASM observations [24]. Our studies suggest that a slow-pulsation magnetized neutron star is located in 4U 2206+54.

2 Observations of INTEGRAL/IBIS and RXTE/ASM

The hard X-ray source 4U 2206+54 was observed during the INTEGRAL pointed observations of the Cassiopeia A region around December 2005. The hard X-ray flare were captured by the low-energy detector (called ISGRI) of the Imager (IBIS) aboard INTEGRAL. we derived the hard X-ray light curve of 4U 2206+54 in the band of 20 – 40 keV from 2005 Dec 11 to Dec 19 (see Fig. 1). A strong hard X-ray outburst was detected around Dec 15 – 16, 2005, which lasted $\sim 10^5$ s.

RXTE had no pointed observations on the source 4U 2206+54 during December 2005. Fortunately the source was regularly monitored by the All Sky Monitor (ASM) onboard RXTE. We obtained the dwell-by-dwell light curve (1.5 – 12 keV) of 4U 2206+54 during the hard X-ray flare (Fig. 1). ASM data just filled up the data gap before the hard X-ray flare obtained from the IBIS data. Therefore, the complete observed features of the super-long duration hard X-ray flare in 4U 2206+54 were derived by using both ASM and IBIS observations.

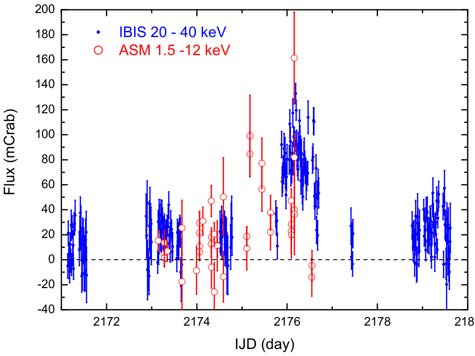

Figure 1: Hard X-ray lightcurves of 4U 2206+54 from Dec 11 to 18, 2005 in the energy ranges of 1.5 -12 keV derived with the RXTE all sky monitor (ASM) archival data and 20-40 keV observed by INTEGRAL/IBIS (IJD is the INTEGRAL day starting at 2000 Jan 1). The flux unit of 1 Crab corresponds to 2.2×10^{-8} erg cm^{-2} s^{-1} in the band of 1.5 -12 keV and 7.6×10^{-9} erg cm^{-2} s^{-1} in the 20-40 keV band. The hard X-ray burst occurred at UT 2005 Dec 15.1085 and lasted $\sim 1.5\times10^5$ sec.

3 Properties of 4U 2206+54 during the flare

The entire light curve of the hard X-ray flare in 4U 2206+54 detected by both INTEGRAL/IBIS and RXTE/ASM was presented in Fig. 1. The hard X-ray flare occurred at UT 2005 Dec 15.1085 and lasted over 2 days. This peculiar flare showed a double-main-peak feature in the light curve.

The first peak only captured by the ASM data had a peak flux of $\sim$ 100 mCrab and decayed to $\sim$ 20 mCrab in 13 hours. This peak appeared to have a sharp rise peak and then the flux decayed with a long time of $\sim$ 15 hours. ASM data covered three energy bands: 1.5– 3 keV; 3– 5 keV; 5–12 keV. This X-ray flare cannot be detected in the low energy bands below 5 keV. The hardness ratio of 5–12 keV over 1.5–3 keV from ASM data had a peak value of $\sim$ 9 at the start of the flare and then had a long duration soft tail with a hardness ratio of $\sim$ 1.

The second main peak was detected by IBIS, which emitting gamma-ray photons even above 300 keV. IBIS observations showed the detailed variability information in three energy band (Fig. 2): 20 – 40 keV; 40 – 100 keV; 100 – 300 keV. Multiple mini-peak feature also appeared in the second main peak in all energy bands. The power spectrum analysis showed a significant modulation period at $\sim 5550\pm50$ s, which should be due to the pulsation period of the neutron star located in 4U 2206+54 [18, 23]. The folded 20 – 40 keV light curve of 4U 2206+54 at a pulsation period (5550 s) is also shown in Fig. 3. The second peak has a very long duration ($\sim 10^5$ s) with the average flux from 20 – 100 keV is $\sim (9.8\pm0.9)\times10^{-10}$ erg cm^{-2} s^{-1}, corresponding to a mean luminosity of 1.2×10^{36} erg s^{-1} in the range of 20 –100 keV assuming a distance of 3 kpc. Then the total released energy of the flare during the second peak with the duration of $\sim 10^5$ sec is about 10^{41} ergs.

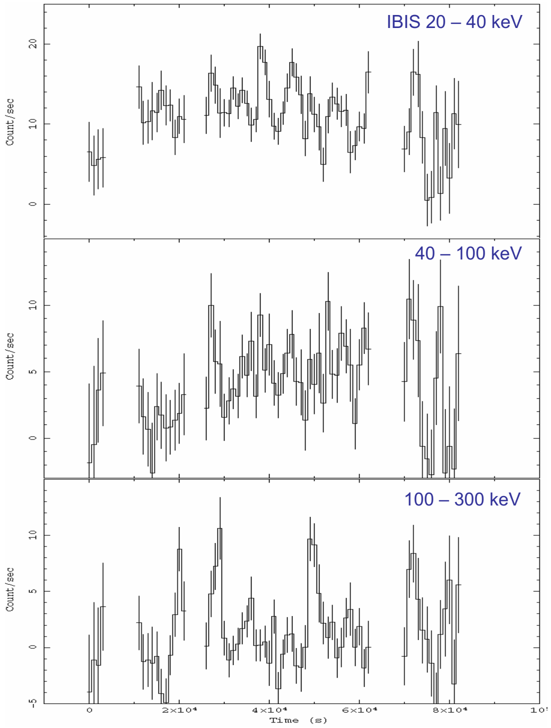

Figure 2: The light curves of the second peak of the hard X-ray flare in three energy ranges of 20 - 40 keV, 40 – 100 keV and 100 – 300 keV starting at Dec 15 UT18:00, 2005 observed by INTEGRAL/IBIS. The modulation period at 5550 s appears in all energy band curves, which should be the spin period of the neutron star.

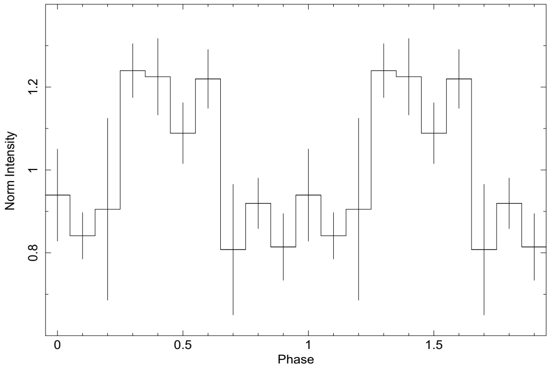

Figure 3: Pulsed profile of 4U 2206+54 in the energy range of 20 – 40 keV by IBIS during the second peak folded at a pulsation period (5550 s).

IBIS also detected the source just before the outburst. The hard X-ray spectral analysis of 4U 2206+54 discovered two

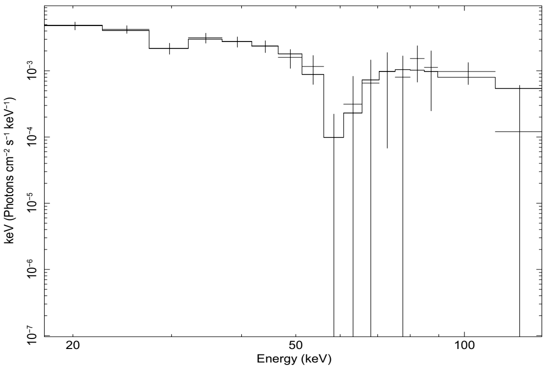

Figure 4: The spectrum of 4U 2206+54 just before outburst from Dec 5 to 12, 2005[23]. It can be fitted by a thermal bremsstrahlung model of $kT \sim 43.1 \pm 2.0$ keV plus two cyclotron resonant absorption lines at $\sim 29.6 \pm 2.8$ keV and $\sim 59.5 \pm 2.1$ keV (reduced $\chi^2 \sim 0.95$, 6 *d.o.f*).

cyclotron resonant absorption lines at $\sim$ 30 keV and 60 keV (Fig. 4), suggesting a magnetized neutron star with a magnetic field of 3×10^{12} G in 4U 2206+54 [23].

4 Discussions on possible origin of the hard X-ray flare

4U 2206+54 as a high mass X-ray binary has a variable X-ray light curve with a luminosity range of $10^{33} - 10^{35}$ erg s^{-1} due to different accretion rates. The luminosity of the hard X-ray flare is much brighter than the normal states of 4U 2206+54, so this flare may require further explanation. The compact object in 4U 2206+54 was recently identified as a magnetic neutron star of $B \sim 3.3 \times 10^{12}$ G (see Fig. 4). The hard X-ray flare could be related to some of the astrophysical processes around the highly magnetized neutron star.

The sudden strong X-ray flares have been detected in some other high mass X-ray binaries (e.g., GX 301-2, see [12]). In these systems, the X-ray flares occur always before periastron passages of the neutron star. Therefore, the flares show the recurrence of orbital periodicity, and have following characteristics: (1) duration of ~ 0.1 orbital phase, roughly several days [12, 13]; (2) strong photoelectric absorption, which makes the flares events absent at low energies (< 5 keV [13]); (3) the spectrum can be described by a cut-off power-law model. So we can check this possible modulation in the X-ray light curve of 4U 2206+54. If we assume the detected X-ray flare occurred around the periastron passage of the neutron star, then the X-ray flares would recur with the recurrence time of ~ 19 days. However according to RXTE/ASM and INTEGRAL/IBIS long monitoring data from Dec 10 2005 – Jan 5 2006, only one flare was detected and no orbital modulation was found. Then the X-ray flare in 4U 2206+54 was different from the outbursts near the periastrons in other sources because the detected hard X-ray flare would not be repeated just because of the orbital modulation.

Some accreting neutron stars show the recurrent Type-1 X-ray bursts. Type 1 X-ray bursts caused by thermonuclear flashes on accreting neutron stars with low magnetic fields ($< 10^{10}$ G) are only observed in low-mass X-ray binaries (LMXBs). In highly magnetized neutron star in high mass X-ray binary, no confirming evidence is observed. An unusual X-ray burst from M28 reported by [9] was suggested to be a subluminous thermonuclear burst in a highly magnetized case. Possibility of thermonuclear flashes on the surface of a strongly magnetized neutron star ($> 10^{12}$ G) was also studied and originally proposed as a model of gamma-ray bursts [26]. We do not exclude the possibility of the thermonuclear origin for the flare in 4U 2206+54.

Recently, some soft gamma-ray time-structured bursts of durations from several hours to about 1 day have been detected by INTEGRAL/IBIS observations in some supergiant high mass X-ray binaries which were called supergiant fast X-ray transients (SFXTs, see [17, 20, 22]). Most of the time, SFXTs are undetectable. And occasionally they undergone fast X-ray transient activity lasting from a few hours to a day. Their outbursts show complex structures characterized by several flares with both rise and decay times of less than 1 hour [20]. In addition, SFXTs differ from other high mass X-ray binaries which are persistent bright X-ray sources with luminosity $> 10^{35}$ erg s^{-1}. While SFXTs have the outburst luminosity of $\sim 10^{35} - 10^{36}$ erg s^{-1} and the quiescent luminosity upper limits of about $10^{32} - 10^{33}$ erg s^{-1} [17].

The SFXTs also belong to the wind-fed accretion systems. The physical origin of the fast outbursts displayed in SFXTs is still unknown. It was suggested that the presence of dense clumps in the wind of OB supergiant companions produces the accretion outbursts in SFXTs [11]. It is believed that SFXTs should contain sporadically accreting neutron stars, then they would be similar to the system of 4U 2206+54. Some of SFXTs have been found to contain a neutron star with pulsation period from ten to a few hundred second [21], and orbital period from several days to 30 days [2]. 4U 2206+54 has a similar orbital period but a much slower pulsation period. And the detected flare in 4U 2206+54 has the similar peak X-ray luminosity to those of SFXTs. But there exist the different effects on accretion by the wind of a main sequence star in 4U 2206+54 and supergiant winds in SFXTs, which needs deeper studies. It should be noted that a small part of unidentified sources show the fast X-ray bursts and are candidate SFXTs though the optical counterpart has not been identified as the early-type supergiant star [17]. Anyway, this hard X-ray flare in 4U 2206+54 could be a *missing* link between these systems, and may help us to understand the nature of SFXTs and the flare of 4U 2206+54.

4U 2206+54 is one of the slowest pulsation neutron star systems. In the $P_{\rm spin} - P_{\rm orbit}$ diagram (see Fig. 5), 4U 2206+54 and the other super-slow pulsation neutron star binary 2S 0114+65 ($P_{\rm spin} \sim 2.6$ hr, $P_{\rm orb} \sim 11.59$ days

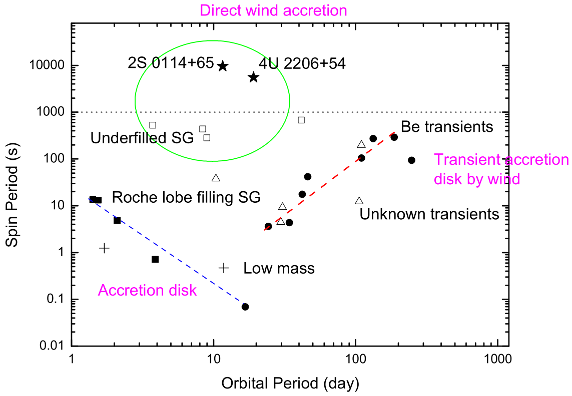

Figure 5: The spin period - orbital period diagram for the accreting neutron star systems (the Corbet diagram[4]). The data are collected by [25]. There exist a positive correlation between $P_{\rm spin} - P_{\rm orbit}$ for the Be transient systems; and a possible negative correlation for the disk-accretion system including Roche Lobe Filling Supergiants and low mass systems; For the underfilled Roche Lobe Supergiants and two long-pulsation systems 2S 0114+65, 4U 2206+54 which all belong to wind-fed accretion systems, the possible relation between $P_{\rm spin} - P_{\rm orbit}$ is different from that of the Be transients.

[25]) have the similar properties to underfilled Roche Lobe Supergiants which are also powered by direct wind accretion. These systems may follow a $P_{\rm spin} - P_{\rm orbit}$ relation quite different from that of the Be transient systems (Fig. 5). 2S 0114+65 and 4U 2206+54 are the only two known super-slow pulsation neutron star high mass X-ray binaries ($P_{\rm spin} > 1000$ s), and two possible super-slow X-ray pulsar candidates were also reported recently: 1E 161348-5055 in a young supernova remnant RCW 103 ($P_{\rm spin} \sim 6.67$ hr [7]), and a wind-accretion symbiotic low mass X-ray binary 4U 1954+319 ($P_{\rm spin} \sim 5$ hr [15]). The formation mechanisms of these super-slow X-ray pulsars are unclear. Li & van den Heuvel [14] have studied the origin of the long pulsation period X-ray pulsars and suggested that a slow period is possible if the neutron star was born as a magnetar with an initial magnetic field $\geq 10^{14}$ G, decaying to a current value of 10^{12} G, allowing the neutron star to spin down to the measured spin period within the lifetime (Myr) of the companion. An alternative formation channel proposed by Ikhsanov [10] showed that an initial magnetic field strength of $B \gg 10^{13}$ G is not necessary if the evolutionary sequence of the neutron star consisted of both supersonic and subsonic propeller phases. Anyway, both scenarios predicted that the equilibrium period for long pulsation period pulsars would be less than half hour, and this spin period will be approached on time scales of < 100 yr for disk accretion and < 1000 yr for stellar wind accretion [10]. The very short time scale suggested that the long pulsation period X-ray pulsars should be very rare. Presently it is fortunate (maybe strange from the probability of detection) that at least three candidates are discovered. However, it is still possible that these super-slow X-ray pulsars are still young systems. Thus the current understanding of the pulsar formation in different systems is quite deficient. Further theoretic work may be required. It is hoped that future observations of the spin-period history of 4U 2206+54 and other similar systems would help us to understand the formation mechanism of the long spin period.

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