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Change in spin-down rate and detection of emission line in HMXB 4U 2206+54 with AstroSat observation

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Abstract. This work presents timing and spectral analysis of 4U 2206+54 using data obtained from LAXPC instrument onboard India's AstroSat mission. This source was observed with AstroSat in September–October 2016. We report detection of 5648 (4) s pulsations at MJD 57669 in the October observation of 4U 2206+54. The pulse profile is sinusoidal and the inherent shape is independent of energy up to 30 keV. The pulse fraction increases with energy from ∼0.5 to ∼0.8%. We report an updated spin-down rate of $2.95(14) \times 10^{-7}$ s s^{-1}. This is about 0.40 times smaller than the previously reported long term value. The energy spectrum is best modeled with an absorbed power-law with high energy exponential cut-off. We have detected presence of broad emission line in 4U 2206+54 at an energy of 7 keV with equivalent width of ∼0.4 keV.

Keywords. X-rays: stars—stars: neutron—pulsars: individual: 4U 2206+54.

1. Introduction

4U 2206+54 was first reported in Uhuru's second catalog and its location was redefined by the Ariel V Sky Survey Instrument (Giacconi *et al.* 1972; Villa *et al.* 1976). 4U 2206+54 is a persistent High Mass X-ray Binary (HMXB), wherein the compact object is accreting matter from a dense wind of an early type star (Steiner *et al.* 1984; Negueruela & Reig 2001). The X-ray light curve shows irregular flaring and ∼9.6 d modulation (Corbet *et al.* 2000; Negueruela & Reig 2001). However, from RXTE and Swift observations, Corbet *et al.* (2007) and Wang (2009) have reported modulation at twice the 9.6 d period. The compact object is a strongly magnetized neutron star spinning slowly at a period of ∼5560 s (Torrejón *et al.* 2004; Reig *et al.* 2009; Wang 2009; Finger *et al.* 2010).

The X-ray spectrum of 4U 2206+54 is typical to a neutron star accreting from the wind of its companion star (Negueruela & Reig 2001). The spectrum is known to be well described with a model comprising of absorbed power-law model with exponential cut-off or with a blackbody plus Comptonization (Masetti *et al.* 2004; Wang 2009). The thermal bremsstrahlung model is also known to describe the 4U 2206+54 spectrum equally well (Saraswat & Apparao 1992). A possible detection of cyclotron resonant feature has also been reported (Masetti *et al.* 2004). The spectral variations are correlated with the intensity variations (Negueruela & Reig 2001). The photon index and the hydrogen column density are anti-correlated with hard X-ray luminosity (Masetti *et al.* 2004).

In this paper, the timing and spectral analyses of 4U 2206+54 have been performed by using the data from Large Area X-ray Proportional Counter (LAXPC) onboard AstroSat. The paper is organized as follows. Section 2 describes the observation details and the reduction process of the raw data. In Section 3, we discuss the timing analysis of 4U 2206+54. The results from spectral analysis are presented in Section 4. We discuss our results in Section 5.

2. Observations

AstroSat was launched in September 2015 by Indian Space Research Organization (Agrawal 2006; Singh *et al.* 2014). The LAXPC onboard AstroSat consists of three co-aligned proportional counters (LAXPC10, LAXPC20 and LAXPC30), which cover a broad energy

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Table 1. Log of AstroSat-LAXPC observations of 4U 2206+54 (with mode: EA and observation span: 88.5 ks).

Observation ID	Observation time (dd-mm-yyyy hh:mm:ss)	Exposure (ks)
9000000644	06-09-2016 01:33:43	46.4
9000000720	08-10-2016 16:11:05	42.4

range of 3–80 keV and have a total effective area of 6000 cm^2 at 15 keV (Yadav *et al.* 2016; Agrawal *et al.* 2017). 4U 2206+54 was observed with AstroSat-LAXPC twice in 2016. Details of observations are given in Table 1. For the present work, we have not used data from LAXPC30 due to gain issues (Antia *et al.* 2017). We have used event analysis (EA) mode data and all events were extracted from top layer of LAXPC10 and LAXPC20 (Sharma *et al.* 2020). We have used the LAXPC software (LAXPCSOFT: version 3.4.3) to process the level 1 data.[1]

The source, and background light curves and spectra were extracted by using the tool `laxpcl1`. The background products were corrected for gain shift by using `backshiftv3`. The solar system barycenter correction was performed by using `as1bary`[2] tool. We eventually used the tool `lcmath` to add background subtracted and barycenter corrected light curves from LAXPC10 and LAXPC20.

3. Timing analysis

The 3–20 keV background subtracted and barycenter corrected light curves of 4U 2206+54 binned with 20 s is shown in Figure 1. The X-ray flux is highly variable and exhibits flare-like activity on short timescales similar to that reported by Negueruela & Reig (2001) for this source and in similar for HMXBs by Yamauchi *et al.* (1990) and Kreykenbohm *et al.* (1999).

We used χ^2 maximization technique to search for spin period in the light curve. Since the spin period is expected to be ∼5560 s, therefore, we folded the time series data over a range of periods (3000–8000 s) with a resolution of 10 s by using the `efsearch` tool of XRONOS sub-package of FTOOLS (Blackburn *et al.* 1999). The upper panel of Figure 2 shows the plot of χ^2 values as a function of trial periods. The period

[1] https://www.tifr.res.in/~astrosat_laxpc/LaxpcSoft.html.

[2] http://astrosat-ssc.iucaa.in/?q=data_and_analysis.

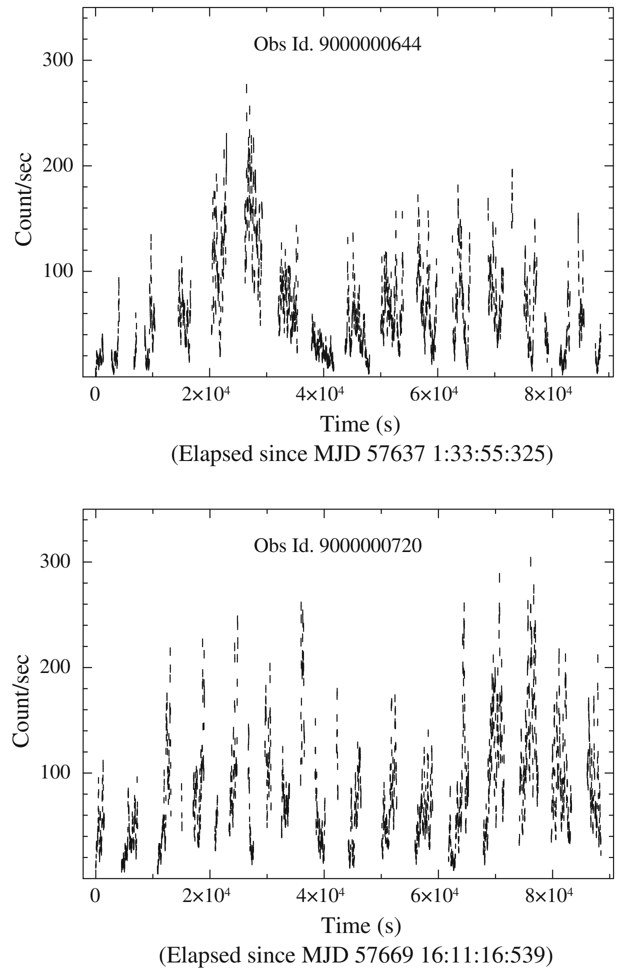

Figure 1. The 3–20 keV background subtracted and barycenter corrected light curves of 4U 2206+54 binned with 20 s.

corresponding to the maximum χ^2 value was modeled with a Gaussian profile. From the best fit, we obtained a spin period of 5608 s with 1σ uncertainty of 4 s. We have detected pulsations only in the October 2016 observation.

We have also used the Lomb–Scargle periodogram method to confirm the periodicity in the unevenly spaced light curve of 4U 2206+54 (Scargle 1982; Press & Rybicki 1989). This method has been successfully used to determine periodicity in several other HMXBs (Laycock *et al.* 2003; Jain *et al.* 2009). As seen in the lower panel of Figure 2, a clear peak is present in the periodogram at a frequency of ∼0.18 mHz. We fitted a Gaussian profile to this peak and obtained a best fit value of the Gaussian center as 0.17706(14) mHz. This corresponds to a pulse period of 5648 (4) s.

We created energy-resolved pulse profiles using the folding technique with the best period (5648 s) obtained above. Figure 3 shows the energy-resolved pulse profiles of 4U 2206+54 in the energy range of 3–6, 6–12,

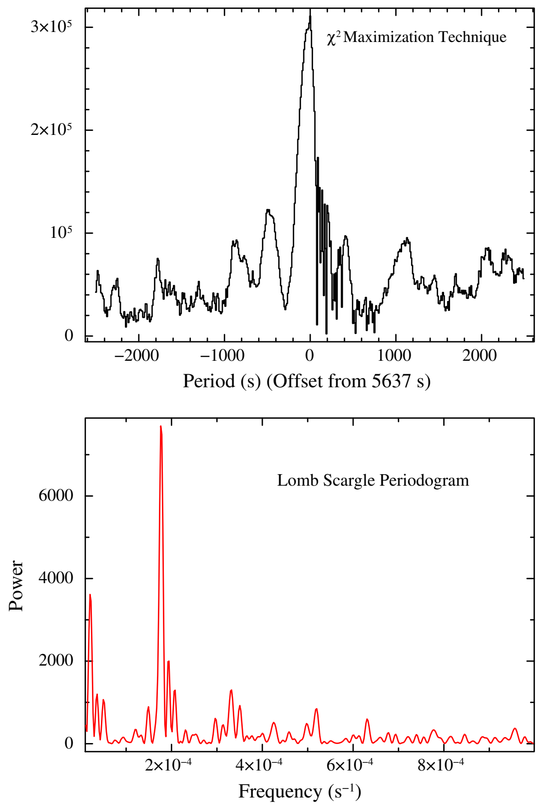

Figure 2. Plots for spin period determination in 4U 2206+54. Upper panel: χ^2 maximization technique. Lower panel: Lomb–Scargle periodogram.

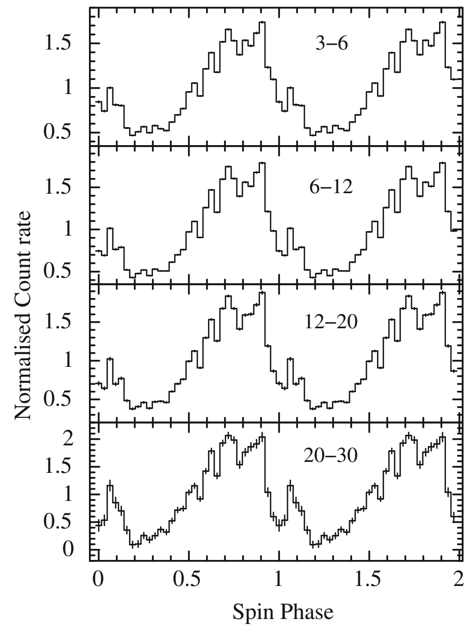

Figure 3. Energy-resolved pulse profile of 4U 2206+54 in the energy range of 3–6, 6–12, 12–20 and 20–30 keV. Two cycles of spin phase have been shown for clarity.

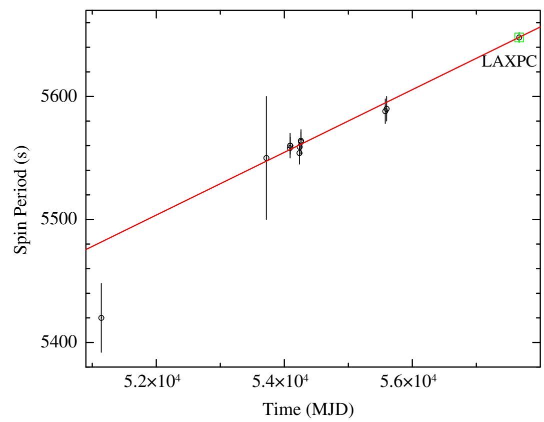

Figure 4. The spin period evolution of 4U 2206+54 from 5420 to 5588 s obtained from Reig *et al.* (2009, 2012), Wang (2009, 2013) and Finger *et al.* (2010). The spin period of 5648 s, determined from this work, is shown with green square symbol.

12–20 and 20–30 keV, respectively. The inherent sinusoidal shape to the pulse profile was observed to be independent of energy. As a function of energy, the fractional amplitude increased from ~0.5 to ~0.8%.

From Suzaku, Beppo-SAX, RXTE, EXOSAT, Integral and XMM-Newton data, Reig *et al.* (2009, 2012), Wang (2009, 2013) and Finger *et al.* (2010) have reported that the spin period of 4U 2206+54 has increased from about 5525 s to about 5588 s. We have observed a further increase to 5648 s in the spin period with AstroSat observation. Our result gives an updated spin-down rate of $\sim 2.95(14) \times 10^{-7}$ s s^{-1}. From numbers fetched from the reported works and the result of the present analysis, Figure 4 shows the long term spin evolution in 4U 2206+54.

4. Spectral analysis

During the 2016 AstroSat observations, 4U 2206+54 was visible above the background up to 30 keV. Therefore, the spectral analysis was done in the energy range of 3–30 keV. Due to systematic differences, we have generated spectrum only from LAXPC20. A systematic uncertainty of 1% was used for the spectral analysis (Antia *et al.* 2017, 2021).

Figure 5 shows the energy spectrum of 4U 2206+54 for both the AstroSat observations. We modeled the spectrum using absorbed power-law with high-energy exponential cutoff. The best fit spectral parameters are given in Table 2. For the observations of October 2016, a broad emission line around 7 keV was also detected with equivalent width of ~0.4 keV. We did not detect any significant emission feature in the September 2016 observation.

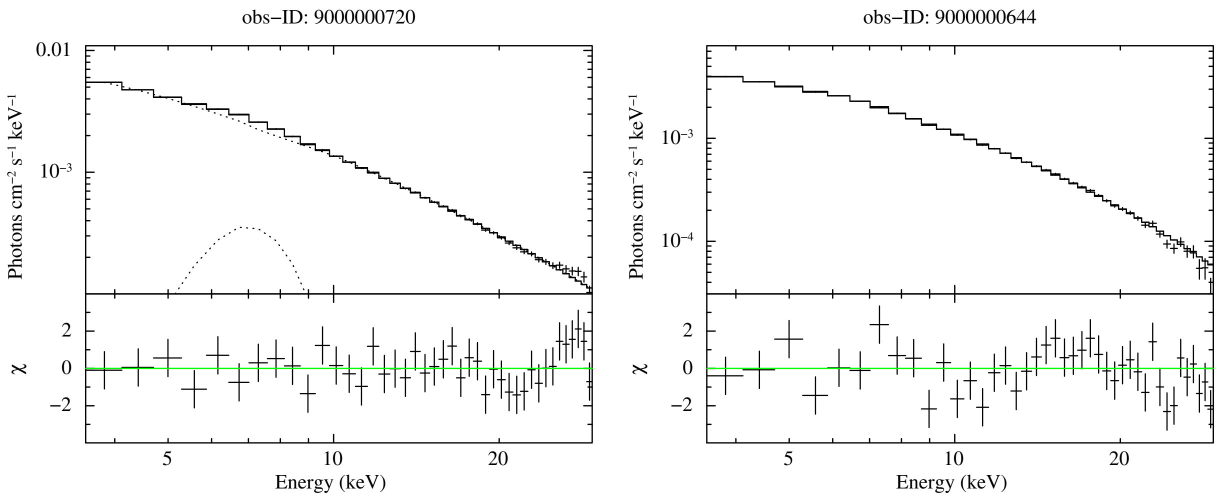

Figure 5. The 3–30 keV energy spectrum of 4U 2206+54.

Table 2. Best fit spectral parameters of 4U 2206+54 from LAXPC observations of September–October 2016. All errors and upper limits reported in this table are at 90% confidence level ($\Delta\chi^2 = 2.7$).

Model	Parameters	October 2016	September 2016
TBabs	N_H (10^{22} cm^{-2})	5.4 ± 1.3	$1.65^{+1.90}_{-1.65}$
HighEcut	$E_{\rm cutoff}$ (keV)	10 ± 2	6.4 ± 0.4
	$E_{\rm fold}$ (keV)	$26.2^{+3.8}_{-4.4}$	$10.4^{+1.3}_{-0.96}$
Powerlaw	Γ	$1.69^{+0.08}_{-0.12}$	$1.04^{+0.15}_{-0.14}$
	Norm	0.070 ± 0.012	$0.017^{+0.006}_{-0.004}$
Gaussian (Fe K)	E (keV)	$7.0^{\rm pegged}$	
	σ (keV)	$1.17^{+0.50}_{-0.45}$	
	Eqw (keV)	$0.422^{+0.421}_{-0.351}$	
	Norm (10^{-3})	$1.14^{+0.75}_{-0.62}$	
Flux[a]	$F_{3-30\ \rm keV}$	4.6×10^{-10}	3.26×10^{-10}
X-ray luminosity[b]	$L_{3-30\ \rm keV}$	3.7×10^{35}	2.6×10^{35}
	χ^2/dof	33.8/35	56.7/37

[a]Unabsorbed flux in the units of erg cm^{-2} s^{-1}. [b]X-ray luminosity in the units of erg cm^{-2}.

The energy spectrum of 4U 2206+54 can also be described well with thermal bremsstrahlung model. For both the observations, the broad 6–7 keV emission line was significantly detectable with an equivalent width of ∼0.4 keV. For the October 2016 observation, the best fit had a χ^2 of 49 for 36 d.o.f. and $kT_{\rm brem}$ was 18 keV. Addition of a thermal blackbody ($kT_{\rm BB} \sim 2.4$ keV) component improved the fit with a χ^2 of 31 for 34 d.o.f. The $kT_{\rm brem}$ increased to ∼25 keV. For the September 2016 observation, we obtained $kT_{\rm BB}$ of ∼3.9 keV.

5. Discussion

This work reports results from the analysis of AstroSat-LAXPC data of 4U 2206+54. From the timing analysis, we have detected 5648(4) s pulsations at MJD 57669. Combining our results with known measurements spread across ∼18 years, we confirm that this long period neutron star is spinning down at a rate of 2.95(14) × 10^{-7} s s^{-1}. Long spin period and the observed spin-evolution rate confirm the magnetar scenario, wherein the neutron star had a high magnetic field strength (~10^{14} G) at birth (Li & van den Heuvel 1999; Finger *et al.* 2010), which has resulted in spinning down the compact object to current value. The observed spin-down rate is about 0.40 times smaller than the reported rate (Finger *et al.* 2010; Reig *et al.* 2012; Wang 2013). It should be noted that since the spectral parameters (except absorption column density) determined in this work are similar to the previously reported numbers, therefore, the reduction in the spin-down rate in 4U 2206+54 is not associated with a consequential change in the accretion geometry just like in other HMXBs (Baykal *et al.* 2006). In the absence of any clear evidence, it is difficult to comment at this stage on the correlation of the change in spin-down rate with source luminosity.

From the spectral analysis, we have detected a broad emission line feature at 7 keV. Most of the previous missions have not detected an emission feature except XMM–Newton, where very weak 6.5 keV fluorescence iron lines have been observed (Reig *et al.* 2012). The authors have reported an absorption column consistent with the interstellar value. This implies very small amount of material around the neutron star and hence, a weak detection of emission line. During the AstroSat observation, the absorption column in 4U 2206+54 was larger than that corresponding to interstellar absorption ($N_{\rm H} = 0.55 \times 10^{22}$ atoms cm^{-2}: HI4PI Collaboration *et al.* 2016), thereby indicating an optically thick surrounding medium. Hence, the detection significance of emission line in the AstroSat observation is much more profound compared to previous works.

4U 2206+54 is a highly variable source and its 1–10 keV luminosity is known to vary in the range of ~10^{34}–10^{36} erg s^{-1} (Corbet & Peele 2001; Masetti *et al.* 2004; Torrejón *et al.* 2004; Wang 2009). Even the 3–100 keV luminosity is known to vary by ~10^{35}–10^{36} erg s^{-1} (Wang 2013). We have obtained 3–30 keV luminosity of $L_X \sim 3 \times 10^{35}$ erg cm^{-2} assuming a distance of 2.6 kpc (Blay *et al.* 2006). A long term X-ray monitoring of 4U 2206+54 is necessary to study the evolution of spin period of the compact object. Further investigation of the emission lines is also necessary to understand the properties of circumstellar material surrounding the neutron star. Future observations will also prove to be crucial in understanding the cause for change in the spin-down rate in 4U 2206+54.

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