Timing and spectral studies of the X-ray pulsar 2S 1417–624 during the outburst in 2021

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Abstract
We study the timing and spectral properties of the X-ray pulsar 2S 1417–624 during the recent outburst in January 2021 based on the Neutron Star Interior Composition Explorer (NICER) observation. We also used some early data from the 2018 outburst to compare different temporal and spectral properties. The evolution of the spin period and pulsed flux is studied with Fermi/GBM during the outburst and the spin-up rate is found to be varied between \( \simeq (0.8–1.8) \times 10^{-11} \text{ Hz s}^{-1} \). The pulse profile shows energy dependence and variability. The pulse profile shows multiple peaks and dips which evolve with energy. The evolution of the spectral state of this source is also studied using the hardness intensity diagram (HID). The HID shows a transition from the horizontal to the diagonal branch, which implies the source went through a state transition from the subcritical to supercritical accretion regime. The NICER energy spectrum is well described by a composite model of a power-law with a higher cut-off energy and blackbody components along with a photo-electric absorption component. An iron emission line is detected near 6.4 keV in the NICER spectrum with an equivalent width of \( \simeq 0.05 \text{ keV} \). The photon index shows an anti-correlation with flux below the critical flux. The mass accretion rate is estimated to be \( \simeq 1.3 \times 10^{17} \text{ g s}^{-1} \) near the peak of the outburst. We have found a positive correlation between the pulse frequency derivatives and luminosity. The Ghosh and Lamb model is applied to estimate the magnetic field at different spin-up rates, which is compared to the earlier estimated magnetic field at a relatively high mass accretion rate. The magnetic field is estimated to be \( \simeq 10^{14} \text{ G} \) from the torque-luminosity model using the distance estimated by Gaia, which is comparatively higher than most of the other Be/XBPs.

Keywords Accretion · Accretion disks - star: pulsar · Individual: 2S 1417–624

1 Introduction
The X-ray transient pulsar 2S 1417–624 was discovered using the Small Astronomy Satellite (SAS–3) in 1978 (Apparao et al. 1980). Several outbursts from the source were observed by the Burst and Transient Source Experiment (BATSE) and the Rossi X-ray Timing Explorer (RXTE) (Finger et al. 1996a; Gupta et al. 2018). Earlier, an X-ray pulsation at \( \sim 17.5 \text{ s} \) was detected from the source light curve with an orbital period of \( \sim 42 \text{ days} \) (Finger et al. 1996a). The orbital parameters of the binary system were improved by Raichur and Paul (2010) using RXTE during the giant outburst in 1999. The source is located at a distance of \( \sim 9.9 \text{ kpc} \) provided by Gaia (Bailer-Jones et al. 2018). The accretion-powered X-ray pulsar 2S 1417–624 went through a giant outburst in 2009, and different timing and spectral properties were studied using RXTE (Gupta et al. 2018). During this outburst, the pulse profile showed energy and luminosity dependence, and the pulse profile evolved from a double-peak feature at lower luminosity to a triple-peak feature at higher luminosity and back to a double-peak feature during the decay phase of the outburst. The variation of pulse fraction was studied with flux, which showed an anti-correlation with source flux during the outburst.

During the MAXI observation, the strong energy dependence of the pulse profile was observed, and the four-peaked pulse profile at lower energies evolved into a double peak feature at higher energies. The pulse fraction showed an anti-correlation with luminosity, which was similar to the
previous giant outburst in 2009 (Gupta et al. 2019). Variability in the pulse profile was also observed from the NICER observations, and the pulse profile evolved significantly with luminosity and energy (Ji et al. 2020). The magnetic field was estimated to be $\sim 7 \times 10^{12}$ G for a source distance of $\sim 20$ kpc by considering the spin-up due to the accretion torque.

The critical luminosity ($L_{\text{crit}}$) of a source is crucial in defining two accretion regimes. The source luminosity is lower than the critical luminosity in the subcritical regime, and at the critical luminosity, a state transition from the subcritical to the supercritical regime occurs. Near the critical luminosity, the pulse profile, pulsed fraction, and beaming patterns change significantly. The state transition can be probed using the hardness intensity diagram (HID). During the state transition, the HID shows a transition from the horizontal branch (low luminosity state) to a diagonal branch (high luminosity state), which was observed earlier for several sources (Reig and Nespoli 2013).

During the 2018 giant outburst, 2S 1417–624 was studied using Swift, MAXI (Gupta et al. 2019), NICER (Serim et al. 2022), and Insight-HXMT (Ji et al. 2020). Serim et al. (2022) reported a state transition from a subcritical to a supercritical regime during the 2018 outburst. A significant evolution of different spectral parameters was found near the critical X-ray flux (unabsorbed) of $\sim 0.7 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ using NICER observations (0.8–12 keV).

Recently, the source went through an outburst in 2021 that was the strongest after the giant outburst of 2018. The outburst was detected by Fermi/GBM, Burst Alert Telescope (BAT) onboard Swift, and Gas Slit Camera (GSC) onboard MAXI on January 2021 (Hazra et al. 2021). The X-ray flux started to increase from the early last week of January 2021, and the duration of the outburst was nearly three months. In this paper, we study the timing and spectral properties of the pulsar 2S 1417–624 during the recent outburst in 2021 using NICER observations and compare different timing and spectral properties with the giant outburst of 2018. We describe the data reduction and analysis method in Sect. 2. We have presented the results of the current study in Sect. 3. The discussion and conclusion are summarized in Sect. 4 and 5 respectively.

2 Observation and data analysis

We detected an outburst from the X-ray pulsar 2S 1417–624 and followed the evolution of the outburst using different instruments. We use data from all-sky X-ray monitors like Swift/BAT (15–50 keV), MAXI/GSC (2–20 keV), and Fermi/GBM (12–50 keV). We analyzed the NICER data during the rising phase of the 2021 outburst near the peak. We used the HEASOFT v6.27.2 for the data reduction and analysis. BAT onboard the Swift observatory (Gehrels et al. 2004) is sensitive in hard X-ray (15–50 keV) (Krimm et al. 2013). We have used the results of the BAT transient monitor during the outburst, which were provided by the BAT team. BAT flux reached a maximum of $\sim 0.1$ Crab during the first week of February 2021.

We have made use of MAXI/GSC (2–20 keV) light curves data (Matsuoka et al. 2009) to follow up on the outburst and to study the evolution of spectral states. MAXI in-orbit operation was started in 2009, and nearly 300 pre-registered sources have been monitored at regular intervals in different energy bands (2–4 keV, 4–10 keV, and 10–20 keV bands). The data provided by MAXI/GSC is averaged for every day. We have studied the evolution of the hardness of the X-ray pulsar using data from different energy bands.

The Neutron Star Interior Composition Explorer (NICER) was launched in 2017 and is currently working as an external payload on the International Space Station. NICER consists of one instrument, the X-ray Timing Instrument (XTI), operating in the soft X-ray region (0.2–12 keV) (Gendreau et al. 2016). A follow-up observation of 2S 1417–624 was conducted by NICER on January 27, 2021, during the rising phase of the outburst, close to the peak of the outburst. The details of the NICER observation are tabulated in Table 1. The processing of raw data has been done using the NICERDAS in HEASOFT v6.27.2. The NICER data are reduced with Calibration Database (CALDB) version xti20200722. We have created clean event files by applying the standard calibration and filtering tool nicerl2 to the unfiltered data. We have extracted light curves and spectra using XSELECT from the barycenter corrected reprocessed clean event file. For the timing analysis, we selected good time intervals according to the following conditions: ISS not in the South Atlantic Anomaly (SAA) region, source elevation $>20^\circ$ above the Earth limb, source direction at least $30^\circ$ from the bright Earth.
For timing analysis, we have applied barycentric corrections to those events using the task barycorr. The ancillary response file and response matrix file of version 20200722 were considered in our spectral analysis. The background corresponding to each epoch of the observation was simulated by using the nibackgen3C50\(^1\) tool (Remillard et al. 2022). Ancillary response files and response matrix files of version 20200722 are considered in our spectral analysis. We have used the latest response files (nixtiere20170601v002.rmf, nixtiavenaxis20170601v004.arf) for the spectral analysis.

The Fermi Gamma-ray Space Telescope operates within a wide energy range between 8 keV–40 MeV. The Large Area Telescope (LAT) and Gamma-ray Burst Monitor (GBM) are the two main instruments onboard the Fermi Gamma-ray Space Telescope (Meegan et al. 2009). The GBM is made up of 14 detectors: 12 detectors of Sodium Iodide (NaI) and 2 detectors of Bismuth Germanate (BGO). In the current study, we have used the spin frequency, frequency derivative, and 12–50 keV pulsed flux measurements with the Fermi/GBM (Finger et al. 2009). The outburst from 2S 1417–624 was also detected with Fermi/GBM from January 2021 and continued for nearly two months with a maximum pulsed flux of \(\sim0.27\) keV cm\(^{-2}\) s\(^{-1}\) on MJD 59260 as provided by Fermi/GBM (Meegan et al. 2009).

The spin-frequencies are also used, which are provided by the Fermi/GBM team. There were a total of 23 spin frequency (\(\nu\)) measurements conducted during our study, and we used 18 measurements, which were at around 3-day equal intervals, and we have not included the first and last few measurements. We used a linear function to fit each of the three consecutive frequency measurements with time. The spin-up rate was calculated from the slope of the linear function during a 9-day interval, as each pulse frequency measurement was collected every 3-day interval, using the \(\chi^2\) minimization technique. We repeated this process for the next three frequency measurements and so on (viz. Kabiraj and Paul (2020)). Therefore, we had 6 spin-up rates from 18 spin frequencies.

We have used the average value of total flux for three consecutive points over the same intervals, which are used to determine \(\nu\). Finally, the luminosity is estimated from the X-ray flux for a distance of \(\sim9.9\) kpc. X-ray luminosity of the source is calculated from the count rate history provided by Swift/BAT team (Krimm et al. 2013) by multiplying a flux conversion factor of \(1.13 \times 10^{-7}\) erg cm\(^{-2}\) s\(^{-1}\) (Ji et al. 2020).

### 3 Results

The X-ray pulsar 2S 1417–624 went through an outburst during January-March 2021, detected by Fermi/GBM, Swift/BAT,\(^2\) MAXI/GSC, which reached a maximum flux during the second week of February 2021. Figure 1 shows the variation of hard X-ray flux during the outburst using Swift/BAT (15–50 keV). The total duration of the outburst was around 3 months, which started in early January 2021 and continued till March 2021. We have summarized the results of the timing and spectral analysis of 2S 1417–624 during the recent outburst in 2021. We have used MAXI (Mat-suoka et al. 2009) final data products (light curves) as well as the Fermi (Finger et al. 2009; Meegan et al. 2009) pulse frequencies and pulsed flux evolution data for this source.

#### 3.1 Variation of pulse profile and pulsed fraction

The light curves were produced using the science event data in different energy ranges with a bin size of 0.1 s from NICER data. We used the effsearch task in FTOOLS to check for the periodicity in the time series of the barycenter and background corrected data sets. We used the fold-

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\(^{1}\)https://heasarc.gsfc.nasa.gov/docs/nicer/tools/nicer_bkg_est_tools.html

\(^{2}\)https://swift.gsfc.nasa.gov/results/transients/.
Fig. 2 The pulse profile of 2S 1417–624 using NICER/XTI. The left side image shows a pulse profile (0.4–10 keV) during the 2021 outburst (Obs. ID–3200130112) and the right side image shows a pulse profile (0.4–10 keV) during the 2018 outburst (Obs. ID–1200130104) at comparable flux level.

Fig. 3 Energy-dependent pulse profiles of the X-ray pulsar 2S 1417–624 using NICER/XTI observations. The left-hand side figure shows the energy-dependent profile during the 2021 outburst and the right-hand side figure shows the energy-dependent profile during the 2018 outburst (NICER Obs. 7).

We have studied the variation of different timing properties of the X-ray pulsar 2S 1417–624 during the outburst using NICER observations. The spin period of the pulsar during the outburst is found to be $P = 17.3649 \pm 0.0001$ s using NICER data, which is comparable with the pulse period recorded with Fermi/GBM during the outburst. Fermi/GBM found that the period decreased slowly with the time of the outburst. Figure 2 shows the pulse profile using NICER data in the energy range of 0.4–10 keV, which consists of multiple broad peaks and narrow dips. We have compared pulse profiles with the 2018 outburst at the comparable flux level. The left side of Fig. 2 shows the pulse profile during the 2021 outburst, and the right side of Fig. 2 shows the pulse profile during the 2018 outburst.

We have looked at the energy dependence of the pulse profiles as well as the temporal variation of the pulse profile during the outburst. Figure 3 represents the energy-dependent pulse profile for four different energy ranges. The variation of the pulse profile over four energy bands:

3https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.
0.4–2 keV, 2–3 keV, 3–4 keV, and 4–6 keV is shown in Fig. 3. We have also estimated the pulse profile in the 6–10 keV band, but due to the low count rate in this band, we have not included this. The pulse profile shows two broad peaks and dips, which varied with energy. The pulse profile of the first row (0.4–2 keV) of Fig. 3 shows two clear dips and two broad peaks. We compare the energy-resolved pulse profile with the previous giant outburst of 2018 at comparable flux levels, which also showed two broad peaks and dips which evolved slightly with energy.

For estimating the pulsed fraction, we used this formula:

$$PF(\%) = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \times 100$$  \hspace{1cm} (1)

where $I_{\text{max}}$ and $I_{\text{min}}$ are the maximum and minimum intensities respectively in the folded light curve.

Figure 4 shows the variation of pulsed fraction for different energy ranges for which the energy-resolved pulse profile is studied. The horizontal bars represent the energy ranges for which the PF is calculated, and the vertical bars indicate the corresponding error in measurements. We have compared the value of pulse fraction at the same energy ranges with the 2018 and 2021 outbursts.

We have estimated the pulsed fraction for a few earlier Nicer observations during the 2018 outburst. Table 1 (5th column) summarizes the value of the pulsed fraction. The pulsed fraction shows a trend to decrease with an increase in flux. The first row of the table corresponds to the 2021 outburst and the rest of the rows are during the 2018 outburst. The right-hand side image of Fig. 10 shows the variation of pulsed fraction with flux. This indicates that the pulsed fraction is decreased with an increase in X-ray flux. Figure 5 shows the evolution of the spin frequency and pulsed flux (12–50 keV) during the outburst of 2021 using Fermi/GBM, which implies that the pulse period of the X-ray pulsar has decreased slowly with time. We estimated the spin frequency derivative (as described in Sect. 2), which varied between ~0.8–1.8 × 10^{-11} Hz s^{-1} during the outburst (shown in the middle panel of Fig. 5).

We have studied the evolution of the spectral state of the source during the outburst. Figure 6 shows the variation of flux using Swift/BAT and MAXI/GSC. The top panel of Fig. 6 shows the variation of hard X-ray flux using BAT (15–50 keV), which indicates that the flux reached a value of ~0.12 crab near the peak of the outburst. The middle panel of Fig. 6 shows the variation of flux using MAXI (2–20 keV), which indicates that the highest flux was ~0.04 crab near the peak of the outburst. The bottom panel of Fig. 6 shows that the HR varied between 0.1–6 during the outburst.

The hardness ratio shows a significant variation during the outburst. The HR started to increase during the rising phase (from MJD 59216) and has continued to increase and reached a maximum value of ~6 near the peak of the outburst (MJD 59256), after that, the HR started to decrease. We have also studied the hardness intensity diagram using Swift/BAT and MAXI flux. Figure 7 shows the hardness intensity diagram (HID) for 2S 1417–624 during the outburst. The HID shows that there is a sudden turn towards the left above the critical luminosity. The low luminosity states are represented by the horizontal branch (HB) and the high luminosity states are shown by the diagonal branch (DB). This sudden turn above the critical luminosity implies a state transition from subcritical to supercritical for this source.

Figure 8 shows the variation of spin-up rate with luminosity. A power law is used to fit the $\dot{v}$ and luminosity. This shows a positive correlation between the spin-up rate and the luminosity. Spin frequency derivatives vary between ~(0.8–1.8) × 10^{-11} Hz s^{-1}, which is estimated from spin frequency evolution history as provided by Fermi/GBM. The luminosity is varied between ~(1.0–3.5) × 10^{37} erg s^{-1}, which is estimated from the Swift/BAT count rate using a multiplying factor.

### 3.2 Energy spectrum

The spectra were produced using the NICER (0.8–12 keV) data. We have excluded the spectrum above 12 keV and below 0.8 keV due to the poor source count rate statistics in these ranges. The NICER spectra were fitted using XSPEC v12.11.0 and model parameters were varied independently. We tested different simple single-component models like high energy cut-off power-law, bbody, and compTT as well as combinations of models like...
Fig. 5 The top panel shows the variation of pulse frequency ($\nu$) of 2S 1417–624 during the outburst using Fermi/GBM. The pulse frequency estimated using NICER is shown with a red asterisk. The middle panel represents the variation of frequency derivatives ($\dot{\nu}$), which is estimated from Fermi/GBM spin period evolution history. The bottom panel shows the evolution of pulsed flux (12−50 keV) in the unit keV cm$^{-2}$ s$^{-1}$ using Fermi/GBM. The vertical bars represent errors in corresponding measurements.

Fig. 6 The top row shows the evolution of flux using Swift/BAT and the middle row represents the evolution of flux using MAXI/GSC during the outburst of 2021. The bottom row shows the variation in the hardness ratio (BAT/MAXI) during the outburst.

Fig. 7 Hardness intensity diagram using BAT and MAXI flux. The hardness ratio (BAT/MAXI) is estimated during the time MJD 59225−59266 of the outburst. The low luminosity states are represented by the horizontal branch and the high luminosity states are shown by the diagonal branch. A transition from a horizontal to a diagonal branch is visible for this source.

Fig. 8 Variation of spin change rate (in unit of $10^{-12}$ Hz s$^{-1}$) with luminosity (in unit of $10^{37}$ erg s$^{-1}$). The dotted blue line represents the best power-law fit of data points that gives a power-law index of 0.82±0.11.

We have studied the energy spectra using NICER/XTI data and compared the variation of spectral parameters near the same flux levels with the earlier outburst in 2018. Earlier, the spectra of the source were modeled using an absorbed power-law with a high energy cut-off and an iron emission line near 6.4 keV (Gupta et al. 2019). We have applied an absorbed power-law continuum model, and an additional blackbody emission has been introduced, which improves the fit statistics. This model is good enough to describe the spectral continuum at lower flux limits, which be-

power-law+bbody, diskbb+bknpower, and po×highEcut+bbodyrad to fit the source spectra. The spectra were well fitted with a blackbody emission and a power-law component with a high-energy cut-off and an iron emission line at 6.4 keV, also modeled using a Gaussian. The blackbody has been introduced along with a simple power-law to model the soft excess component (Hickox et al. 2004). To find the effect of absorption by hydrogen, all model components were multiplied by a photo-electric absorption model.
Fig. 9 The energy spectrum of NICER (0.8–12 keV) with the best-fitted model $\text{phabs}(\text{powerlaw} \times \text{highEcut} + \text{bbbody} + \text{gaussian})$ during the 2021 outburst. The residual is shown in the bottom panel.

comes more complex at higher flux levels, as observed during the giant outburst of 2018 (Gupta et al. 2019). The additional emission near 6.4 keV is modeled using a Gaussian component, which provides a reduced $\chi^2$ value of $\sim 1.0$.

The energy spectrum with the best-fitted models during the 2021 outburst is shown in Fig. 9 where the bottom panel of Fig. 9 shows the residuals. The energy spectrum of the X-ray pulsar can be well fitted with a high-energy cut-off power-law ($\text{power-law} \times \text{highEcut}$ in XSPEC) and a blackbody emission component $\text{bbbodyrad}$ in XSPEC, along with a photoelectric absorption ($\text{phabs}$ in XSPEC). The NICER spectrum in the energy range 0.8–12 keV is well described with blackbody emission with temperature ($kT_{bb}$) $\sim 0.255$ keV and hydrogen column density $\sim 1.2 \times 10^{22} \text{ cm}^{-2}$.

The unabsorbed X-ray flux in the 0.8–12 keV energy range is $\sim 6.5 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$ using NICER observation during the 2021 outburst. Table 2 summarizes the values of different spectral parameters for the best-fitted model. The $\text{cflux}$ convolution model was used to calculate all of the flux (unabsorbed) values in the paper. All of the reported errors were obtained using the err tool from XSPEC. Uncertainties are given for a 90% confidence interval. We have also looked at the variation of spectral parameters with X-ray flux from different NICER observations in 2018 and 2021.

The photon index decreased as the flux increased and shows an anti-correlation below the flux level of $\sim 7 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, which implies that at the brighter phase of the source the X-ray emission was harder. Near the peak of the outburst during NICER observation, the photon index was $\sim 0.4$. For the sake of comparison, we have used a few earlier NICER data points at nearly the same flux level. The photon index showed a consistent value with the earlier observation at the same flux level. Hydrogen column

| Obs. ID     | Date (MJD) | Count rate (10$^{-3}$ cm$^{-2}$ s$^{-1}$) | Photon index ($\Gamma$) | Equivalent width (keV) | Line energy (keV) | Line flux (10$^{-3}$ cm$^{-2}$ s$^{-1}$) | Reduced $\chi^2$ | NICER unabsorbed flux (erg cm$^{-2}$ s$^{-1}$) |
|-------------|------------|----------------------------------------|-------------------------|------------------------|-----------------|---------------------------------------|----------------|-----------------------------------------------|
| 3200130112  | 5992.50    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |
| 1200130165  | 5992.68    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |
| 1200130155  | 5992.78    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |
| 1200130166  | 5992.88    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |
| 1200130168  | 5992.98    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |
| 1200130104  | 5993.17    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |
| 1200130143  | 5993.20    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |
| 1200130144  | 5993.23    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |
| 1200130175  | 5993.17    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |
| 1200130177  | 5993.18    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |
| 3200130182  | 5993.25    | 39.59±0.08                             | 0.12±0.07               | 1.93±0.16              | 5.83±0.33       | 1.19±0.09                             | 0.45±0.03     | 6.539±0.004                                   |

Table 2 Spectral fitting parameters of 2S 1417–624 for best-fit model using NICER (0.8–12 keV) observations.
density and the blackbody temperature also did not show any significant variation at the same flux level. The radius of the emitting region of the blackbody is estimated using the normalization constant of the model bbodyrad as $R_{km}^2/D_{10}^2$, where $R_{km}$ is the source radius in km and $D_{10}$ is the distance to the source in units of 10 kpc. The BB emission region is found to be $\sim$12 km at a flux level of $\sim 6.54 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ using NICER (0.8–12 keV) observation during 2021 outburst. Earlier, during the 2018 outburst, the BB emission radius was estimated to be $\sim$8 km using NICER observations for a source distance of $\sim 9.9$ kpc using bbodyrad model (Serim et al. 2022) at a flux level of $\sim 19.36 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ in the energy of 0.8–12 keV of NICER. The variation of photon index with flux is shown in Fig. 10, which shows that the photon index is anticorrelated with the X-ray flux below the critical flux level ($\sim 7 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$), which is shown by a vertical dotted line. Above the critical flux, the correlation turns to a slightly positive trend, which may indicate a state transition for this source.

### 4 Discussion

We present the results of timing and spectral analysis of 2S 1417–624 using NICER data during the recent outburst in 2021. The timing analysis reveals that the pulse profile shows multiple peaks and dips with an energy-dependent nature, which is comparable with the previous results at the same flux levels during the giant outbursts in 2009 (Gupta et al. 2018) and 2018 (Ji et al. 2020; Gupta et al. 2019). The energy dependence of the pulse profile is studied to investigate the evolution of the individual dips and peaks of the pulsar with different energies. The pulse profile evolves significantly with energy, which is comparable at the same flux level as the previous result (Ji et al. 2020). During the 2021 outburst, the spin-up rate is found to vary from $0.8 \times 10^{-11}$ Hz s$^{-1}$ to $1.8 \times 10^{-11}$ Hz s$^{-1}$, which is comparable to the previous outbursts of 2S 1417–624 (Finger et al. 1996a; Ji et al. 2020). The mass accretion rate is estimated using the luminosity near the peak (during NICER observation) of the outburst as, $L = \eta \dot{M} c^2$ and $\dot{M} = 1.3 \times 10^{17}$ g s$^{-1}$, which is estimated using the accretion efficiency factor $\eta = 0.2$. The variation of pulsed fraction with energy also shows consistent values at comparable flux levels in the 2018 and 2021 outbursts. The value of the pulsed fraction in the 6–10 keV energy band is not consistent probably due to the low count in this band. The pulsed fraction showed a negative correlation with luminosity. We have used a few earlier NICER data along with recent data to investigate the evolution of pulsed fractions at different flux levels.

Earlier, the X-ray pulsar 2S 1417–624 showed strong luminosity and energy dependence during the 2018 giant outburst. During the present outburst, two broad peaks and dips are observed in the pulse profile, and the pulse profile evolves with energy. The double peak feature, with 0.5 separations of each peak, indicates a simple beam function created from both of the poles of the neutron star during the outburst (Gupta et al. 2018). During the 2018 giant outburst, the luminosity dependency of the pulse profile and the complex shape of the pulse profiles were reported by Ji et al. (2020). In the supercritical regime, an additional dip was observed, probably due to the increased absorption at higher luminosity. It is also possible that the hydrogen column density of the partial covering absorber ($n_{H2}$) may increase due to the absorption of the materials around the neutron star.
as in the case of Swift J0243.6+6124 (Zhang et al. 2019). At higher luminosity, the beam patterns become more complex and mostly dominated by fan-beam or a mix of pencil and fan-beam patterns. During the 2009 giant outburst, Gupta et al. (2019) performed phase-resolved spectroscopy for this source and concluded that except for the primary dip (phase 0.95–1.05) there was no significant variation in the additional column density. Several pulsars showed strong energy and luminosity dependence of the pulse profiles, like 1A 0535+262 (Mandal and Pal 2022), EXO 2030+375 (Epili et al. 2017; Naik et al. 2013), GX 304–1 (Jaisawal et al. 2017; Naik et al. 2013), GX 304–1 (Jaisawal et al. 2017; Naik et al. 2013), and 4U 0115+63 (Becker et al. 2012; Reig and Nespoli 1996b; Bildsten et al. 1997), EXO 2030+375 (Parmar et al. 1989; Reynolds et al. 1996), GRO J1744–28 (Bildsten et al. 1997), and SAX J1213.5+4545 (Baykal et al. 2002) showed correlation between spin-up rate and X-ray flux. Earlier, critical flux level was estimated to be \( \sim 0.7 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \) using NICER (0.8–12 keV) for a source distance of 9.9 kpc (Serim et al. 2022). During the NICER observation of the 2021 outburst, the unabsorbed flux (0.8–12 keV) level was below the critical level. Above this flux level, the source state transition from sub-critical to super-critical accretion regime may occur, and in this regime, the radiation pressure is high enough to halt the accretion flow at a certain height above the pulsar. During this transition, the pulse profile morphology, pulse fraction, and different spectral parameters also show significant variation. The beaming pattern also seems to change from pencil-beam to fan-beam or a mix of pencil and fan-beam (Becker et al. 2012).

Earlier, a correlation between spin-up rate and X-ray flux was observed during outbursts for different transient systems, which was explained in terms of accretion. For example, 2S 1417–624 (Finger et al. 1996a), A 0535+26 (Finger et al. 1996b; Bildsten et al. 1997), EXO 2030+375 (Parmar et al. 1989; Reynolds et al. 1996), GRO J1744–28 (Bildsten et al. 1997), and SAX J1213.5+4545 (Baykal et al. 2002) showed correlation between spin-up rate and X-ray flux. Figure 8 shows that the pulse frequency derivatives of the X-ray pulsar 2S 1417–624 are correlated with luminosity. Earlier, for 2S 1417–624, Finger et al. (1996a) observed that \( \dot{\nu} \) was highly correlated with the pulsed flux. Both these parameters are supposed to be driven by the mass accretion rate.

Based on the accreting torque model and the observed spin-up rate, we have tried to find the magnetic dipole moment and the surface magnetic field of 2S 1417–624. The spin-up rate and the luminosity are known to be correlated in transient X-ray pulsars as (Ghosh and Lamb 1979b; Sugizaki et al. 2017):

\[
\dot{\nu}_{12} = 2.0 n \xi^{1/2} \mu_{30} R_{6}^{2} M_{1.4}^{-3} I_{45}^{-1} L_{37}^{2}
\]

where \( \dot{\nu}_{12} \), \( \mu_{30} \), \( R_{6} \), \( M_{1.4} \), and \( I_{45} \) are the spin frequency derivative, magnetic dipole moment, radius, mass and the moment of inertia of the neutron star given in the units of \( 10^{-12} \text{ Hz s}^{-1} \), \( 10^{30} \text{ G cm}^{3} \), \( 10^{6} \text{ cm} \), \( 1.4 M_{\odot} \), and \( 10^{45} \text{ g cm}^{2} \) respectively. \( L \) is the X-ray luminosity in the unit of \( 10^{37} \text{ erg s}^{-1} \). According to the Ghosh and Lamb (1979a,b) model, under slow-rotator condition, \( n \sim 1.39 \) and \( \xi \sim 0.52 \). Therefore, equation (1) reduces to (Sugizaki et al. 2017):

\[
\dot{\nu}_{12} = k L_{37}^{\alpha}/37
\]

where \( k = 2.0 \mu_{30}^{2} \) and \( \alpha = 6/7. \) For nominal values of \( R_{6} = M_{1.4} = I_{45} = 1 \), measurements of the \( \dot{\nu} \) versus \( L \) give a rough estimation of the magnetic dipole moment of the pulsar. From the \( L \) vs \( \dot{\nu} \) plot, we have estimated \( k \) and \( \alpha \) as 7.65±0.71 and 0.82±0.11 respectively from the best fit result. The estimated value of \( \alpha \) is close to the theoretical...
value. Figure 8 shows the correlation between the spin-up rate and luminosity and the solid line represents the best-fitted result. From the best fit result, we may write the equation (2) as
\[ \dot{\nu}_{12} = (7.65 \pm 0.71) L_{37}^{0.82 \pm 0.11} \]  
(4)

Now the magnetic dipole moment can be written in the form
\[ 2.0 \mu_{30} = 7.65; \mu_{30} \simeq 109 \]  
(5)

The surface magnetic field can be estimated using the magnetic moment (\( \mu_{30} \)) and radius (\( R_b \)) of the pulsar as
\[ \mu_{30} = \frac{1}{2} B_{12} R_b^3 \phi(x) \]  
(6)

\( \phi(x) \) is the correlation factor, for typical NS, \( \phi(x) \sim 0.68 \), the magnetic field can be written as
\[ B_{12} = 2 \times \frac{\mu_{30}}{0.68} \]  
(7)

for \( \mu_{30} \simeq 109 \), the magnetic field is estimated to be \( \simeq 3 \times 10^{14} \text{ G} \).

The high value of the magnetic dipole moment leads to a higher value of the magnetic field (\( \sim 10^{14} \text{ G} \)). Earlier, Ji et al. (2020) also concluded that the estimated magnetic field of this source was high during the 2018 giant outburst. If the source distance is taken as twice (\( \sim 20 \text{ kpc} \) (Ji et al. 2020)) of the Gaia estimated distance, then the magnetic field strength reduces to a typical value of the order \( \sim 10^{12} \text{ G} \). Serim et al. (2022) also concluded that the magnetic field of the source was very high (\( \sim 10^{14} \text{ G} \)) like a magnetar during another study of the 2018 outburst, which is consistent with our results in the 2021 outburst. The high magnetic field in 2S 1417–624 may originate from the limitation of torque models, which do not allow closer distance (Malacaria et al. 2020). There are several sources like XTE J1858+034, GRO J1008–57, GS 0834–430, IGR J18179–1621, IGR J19294+1816, RX J0440.9+4431, MAXI J1409–619, and GRO J2058+42 for which considerable deviations from the GL model were observed, even considering the Gaia measured distances (Malacaria et al. 2020). During the 2009 outburst of 2S 1417–624, the critical luminosity was estimated to be \( \sim 1.33 \times 10^{37} \text{ erg s}^{-1} \) (3–30 keV flux, source distance of 11 kpc) by assuming a magnetic field of \( 0.9 \times 10^{12} \text{ G} \) (Inam et al. 2004; Gupta et al. 2018). Serim et al. (2022) found that the critical flux during the 2018 outburst was \( \sim 7 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \) above which spectral parameters showed significant evolution. We have found that the critical flux (0.8–12 keV) during the 2021 outburst to be \( \sim 7 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \), which is consistent with the previous outburst (Serim et al. 2022). We have also estimated the magnetic field corresponding to the critical luminosity using equation 8, during the 2021 outburst of the source.

The magnetic field corresponding to the critical luminosity \( 0.82 \times 10^{37} \text{ erg s}^{-1} \) is estimated to be \( 0.57 \times 10^{12} \text{ G} \) for a source distance of 9.9 kpc (Bailer-Jones et al. 2018). For a typical neutron star, the critical luminosity and magnetic field are associated as (Becker et al. 2012),

\[ L_{\text{critical}} = 1.5 \times 10^{37} \left( \frac{B}{10^{12} \text{ G}} \right)^{\frac{16}{37}} \text{ erg s}^{-1} \]  
(8)

Using the torque luminosity model, the magnetic field was estimated to be \( \sim 7 \times 10^{12} \text{ G} \) and the distance was estimated to be \( \sim 20 \text{ kpc} \) (Ji et al. 2020).

Earlier, in 2013, Chandra observed 2S 1417–624 during the quiescent phase. The pulsar spectrum was characterized by either a power-law or a blackbody model with a high temperature of \( \sim 1.5 \text{ keV} \) (Tsygankov et al. 2017). The spectrum of the source during the 2021 outburst was well explained by a composite model of power-law and blackbody components. During the 2018 giant outburst, the source spectrum was well explained with the cut-off power-law continuum model and a blackbody component with the interstellar absorption (Gupta et al. 2019). The energy spectrum (NICER/XTI) of the source during the recent outburst in 2021 is also well described with a similar type of model as observed earlier. We have compared the spectral properties of the X-ray pulsar with the 2018 giant outburst at a comparable flux level. Earlier, the photon index showed an anti-correlation with flux below \( \sim 0.7 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \). Such an anti-correlation was also observed in both the 1999 (Inam et al. 2004) and 2009 outbursts (Gupta et al. 2018). During the recent outburst of 2021, the NICER flux was below the critical value (\( \sim 0.7 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \)), and the photon index showed an anti-correlation with X-ray flux below critical luminosity. During the 2018 outburst, Serim et al. (2022) also found an anti-correlation between the photon index and flux below the critical flux value, which turns into a slightly positive correlation above the critical value of flux. We have compared the NICER spectra during the 2018 and 2021 outbursts at comparable flux levels, and the results show consistent values of spectral parameters and the photon index decreases with the increase of X-ray flux and the spectrum gets harder.

We have found the radius of the emitting region of the pulsar using the fitting parameters. The normalization constant of the bbodyrad model gives the size of the emission region for a known distance to the source. From the results of spectral fitting during the 2021 NICER observation, the radius of the emitting region is \( \sim 12 \text{ km} \) for a distance of \( \sim 9.9 \text{ kpc} \).

Earlier, a significant change in the correlation of the \( L–\Gamma \) diagram was seen in different sources near the critical luminosity. The transition from a negative to positive correlation was seen in the \( L–\Gamma \) diagram as luminosity increases above the critical luminosity (Reig and Nesp...
In the subcritical regime, a negative correlation was reported for the sources like 1A 1118–612, GRO J1008–57, XTE J0658–073, and a transition in the correlation of $L \propto \Gamma$ was observed for the sources 1A 0535+262 (Mandal and Pal 2022), 4U 0115+63, EXO 2030+375 (Epili et al. 2017; Jaisawal et al. 2021), 2S 1417–624 (Serim et al. 2022), and KS 1947+300 (Reig and Nespoli 2013). In the subcritical accretion regime, the negative correlation implied the hardening of the power-law continuum with flux. In the supercritical accretion regime, the positive correlation implied the softening of the power-law continuum with flux.

5 Conclusions

We have summarized the results of the timing and spectral analysis of the X-ray pulsar 2S 1417–624 during the outburst in 2021. The spin-up rate varied between $\sim 0.8–1.8 \times 10^{-11}$ Hz s$^{-1}$ during the outburst. A positive correlation is observed between the spin-up rate and luminosity during the outburst. The torque-luminosity model gives a surface magnetic field of the pulsar of $\sim 10^{14}$ G. The higher magnetic field may arise due to the closer distance as given by Gaia. The pulse profile showed multiple peaks and dips, which evolved with energy. The energy spectrum of the source was well described with a composite model consisting of a power-law with higher cut-off energy and a thermal blackbody component. The radius of the emitting region of the pulsar is estimated to be $\sim 12$ km. The photon index showed an anti-correlation with X-ray flux below the flux level of $\sim 7.0 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. During the outburst, the source state evolved from a subcritical to a supercritical regime. The HID supported the state transition. A transition from the horizontal to the diagonal branch is observed from the HID. As flux increased, the spectrum became harder in the horizontal branch and softer in the diagonal branch.

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Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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