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NuSTAR view of Be/X-ray binary pulsar 2S 1417−624 during 2018 giant outburst

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ABSTRACT
We report the results obtained from a detailed timing and spectral studies of Be/X-ray binary pulsar 2S 1417−624 using data from Swift and NuSTAR observatories. The observations were carried out at the peak of a giant outburst of the pulsar in 2018. X-ray pulsations at \( \sim 17.475 \) s were detected in the source light curves up to 79 keV. The evolution of the pulse profiles with energy was found to be complex. A four-peaked profile at lower energies gradually evolved into a double-peak structure at higher energies. The pulsed fraction of the pulsar, calculated from the NuSTAR observation was found to follow an anticorrelation trend with luminosity as observed during previous giant X-ray outburst studies in 2009. The broad-band spectrum of the pulsar is well described by a composite model consisting of a cut-off power-law model modified with the interstellar absorption, a thermal blackbody component with a temperature of \( \approx 1 \) keV, and a Gaussian function for the 6.4 keV iron emission line. Though the pulsar was observed at the peak of the giant outburst, there was no signature of presence of any cyclotron line feature in the spectrum. The radius of the blackbody emitting region was estimated to be \( \approx 2 \) km, suggesting that the most probable site of its origin is the stellar surface of the neutron star. Physical models were also explored to understand the emission geometry of the pulsar and are discussed in the paper.

Key words: stars: magnetic field – stars: neutron – pulsars: individual: 2S 1417-624 – X-rays: binaries – X-rays: stars.

1 INTRODUCTION
Be/X-ray binary pulsars (XBPs) are known to exhibit two types of X-ray outbursts, such as Type I and Type-II X-ray outbursts (Paul & Naik 2011; Reig 2011). Type-I outbursts are periodic X-ray events that usually occur at the periastron passage of the neutron star in the Be/X-ray binary systems. These events last for \( \sim 20–30 \) per cent duration of the binary orbit during which the peak X-ray luminosity of the pulsar reaches as high as \( \sim 10^{37} \) erg s\(^{-1}\). However, there are X-ray outbursts observed from these BeXBPs during which the peak luminosity exceeds \( 10^{37} \) erg s\(^{-1}\). These events are known as Type-II X-ray outbursts. These events are observed occasionally for a duration of a few weeks to a few months and are independent of the orbital phase of the binary. Irrespective of the outburst type, the observed X-ray radiation from the pulsars originates from hotspots at the magnetic poles of the pulsar and/or from column-like structures mounted on the surface of the magnetized neutron stars. These column-like structures are called accretion columns which are formed due to the channelling of accreted matter by the magnetic field of the neutron stars.

During the process of accretion, matter gains sufficient amount of kinetic energy as it approaches the magnetic poles of the neutron star. Corresponding amount of energy is released in the form of thermal radiation when the matter hits the poles of the neutron star (Basko & Sunyaev 1976; Becker et al. 2012). The process of interaction and geometry of the emitting regions at the magnetic poles of the neutron star depends on the mass accretion rate (luminosity) of the pulsar. At low-mass accretion rate, the hotspots at the magnetic poles of the neutron star is the source of X-ray emission. At higher mass accretion rate, a radiation-dominated shock front appears in the accretion column that shapes the X-ray emission through bulk and thermal Comptonization processes from these sources. Depending on mass accretion rate, a transition between subcritical and supercritical regimes (Basko & Sunyaev 1976; Becker et al. 2012; Mushotzky et al. 2015) is also known in several X-ray pulsars such as V 0332+53 (Doroshenko et al. 2017), EXO 2030+375 (Epili et al. 2017) and Swift J0243.6+6124 (Wilson-Hodge et al. 2018). The transition between above two regimes is observed in terms of changes in the shape of pulse profiles (emission geometry) of the pulsar and its spectral index.
The transient Be/XBP 2S 1417–624 was discovered with the third Small Astronomy Satellite (SAS-3) observations in 1978 (Apparao et al. 1980). It was successively detected with other space missions and recognized as 4U 1416–62 and MX 1418–61 (Forman et al. 1978; Markert et al. 1979). The analysis of SAS-3 archival data revealed a coherent pulsation of \( \sim 17.64 \) s from the pulsar (Kelley et al. 1981). Later in 1979, observations with high-resolution imaging detector (HIRI) detector onboard Einstein X-ray observatory provided the precise estimate of the source position. The optical companion was then identified to be a Be star located at a distance of 1.4–11.1 kpc (Grindlay, Petro & McClintock 1984). Like other Be/XBPs, 2S 1417–624 also exhibits Type I and Type II X-ray outbursts. Five Type II and a number of Type I outbursts have been detected from 2S 1417–624 so far (Kelley et al. 1981; Finger, Wilson & Chakrabarty 1996; Inam et al. 2004; Gupta et al. 2018; Nakajima et al. 2018; Krimm et al. 2018). The source has also been monitored during its quiescence phase in 2013 May (Tsygankov et al. 2017a).

Following its discovery in 1978, 2S 1417–624 remained in quiescence for about 16 yr until a second giant outburst occurred in 1994 August. The giant outburst lasted for about 110 d and subsequently followed by five smaller Type I outbursts until 1995 July (Finger et al. 1996). BATSE onboard the Compton Gamma Ray Observatory (CGRO) continuously monitored the source during this period and the binary orbital parameters of the system were determined. The orbital period and eccentricity of the binary was found to be 42.12 d and 0.446, respectively (Finger et al. 1996). The mass function of the system was also derived from the BATSE data which put a lower limit of 5.9 \( M_\odot \) on the mass of optical companion. The binary orbital parameters of the system were later refined by Raichur & Paul (2010), using data obtained from the RXTE observatory during the third giant outburst of the pulsar in 1999. Using the same set of observations (spanning a duration between 1999 November and 2000 August), Inam et al. (2004) reported the intensity dependent pulse profiles and pulsed fraction of the pulsar. The pulsed fraction was found to be correlated with the source flux and the pulse profiles consisted of two peaks, separated by a phase difference of \( \sim 0.5 \). Also, the pulsar was observed to spin-up significantly during the outburst, which was interpreted as a sign of disc accretion.

The fourth giant outburst from the pulsar was observed in 2009 November, reaching a peak intensity of \( \sim 300 \) mCrab in 15–50 keV energy band of Swift/Burst Alert Telescope (BAT, Krimm et al. 2009). The complete outburst was regularly monitored with the RXTE. Analysis of these observations revealed a peculiar evolution of the pulse profiles and pulsed fraction with the source luminosity. The pulsed fraction was found to be anticorrelated with the source flux and pulse profiles evolved from double- to triple-peaked structure with increase in the source luminosity. Also, the energy resolved pulse profiles were found to exhibit a complex evolution. These observed changes were attributed to the change in beam pattern of the pulsar from pencil beam to a mixture of pencil and fan beam geometry (Gupta et al. 2018).

The X-ray spectrum of the pulsar has often been modelled with an absorbed power law (PL) modified with a high-energy cut-off (HECut, Finger et al. 1996; Inam et al. 2004), during its Type I and Type II outbursts. An additional iron line complex in \( \sim 6.4–6.8 \) keV range was also detected during 1999 giant outburst (Inam et al. 2004). However, a cut-off PL model was found to describe the continuum equally well in later observations of 2S 1417–624 during the Type II outburst in 2009 (Gupta et al. 2018). Recently, Chandra observed 2S 1417–624 in 2013 May during the quiescent phase.

2 OBSERVATIONS AND ANALYSIS

Fig. 1 shows the monitoring light curve of 2S 1417–624 during its 2018 giant X-ray outburst, as recorded by Swift/BAT (Krimm et al. 2013). Arrow mark at the peak of the outburst (MJD 58240.57) indicates the beginning of the NuSTAR observation of the pulsar. Swift/X-Ray Telescope (XRT) observed the same outburst for an effective exposure of \( \sim 1.8 \) ks simultaneously (MJD 58240.81) with the NuSTAR observation. A log of all the observations used in the present work is listed in Table 1. We have also used an RXTE/PCA (Jahoda et al. 1996) light curve of 2S 1417–624 during the peak of 2009 outburst (ObsID 94032-02-04-01), for the pulse profile analysis which is presented in Section 3. Standard-1 binned mode data of PCA was used to extract the source light curve in 2–60 keV energy range with a time resolution of 0.125 s. After correcting for background contamination, barycentric correction was applied on the source light curve (see Gupta et al. 2018 for the detailed reduction procedures). While the description of NuSTAR and Swift data reduction procedure is presented below.
Events were reprocessed by using XRTPIPELINE. Standard procedures timing mode during the observation of 2S 1417−624 used in the present work. Barycentric correction was then applied on the background subtracted light curves. The $\chi^2$-maximization technique (Leahy 1987) was utilized to estimate the spin period of the pulsar. Pulsations at a period of 17.475(6) s were detected in the source light curve. We also estimated the pulse period of the pulsar as 17.47(5) s, from the simultaneous Swift/XRT observation of the pulsar (see Section 2.2 for reduction procedures). The error on pulse period is estimated by fitting a Gaussian function on the chi-squared versus period distribution and is quoted for 1$\sigma$ level.

We also estimated the spin period of the pulsar by using independent methods such as CLEAN (Roberts, Lehar & Dreher 1987) and Lomb-Scargle periodogram (Lomb 1976; Scargle 1982; Horne & Baliunas 1986) as implemented in the PERIOD program distributed with STARLINK Software Collection2 (Currie et al. 2014). A consistent value of spin period of 17.475(1) s was obtained from above methods. We then calculated the false alarm probability (Horne & Baliunas 1986) in order to check the significance of the power peak in the periodogram which was found to be above 95 percent. Note that the uncertainty given by these methods corresponds to the minimum error on the period. It is also worth mentioning that the error on the estimated period is very difficult to calculate. Only reliable estimate could be from the simulation of large number of light curves via Monte Carlo or randomization methods (see e.g. Boldin, Tsygankov & Lutovinov 2013). Based on the agreement between estimated period from independent methods, we adopted 17.475(6) s (larger value of error among all the methods) as the spin period of 2S 1417−624 in our study. Pulse profiles were then constructed by folding the light curves at this period.

In order to understand the evolution of pulse profiles with luminosity, an RXTE observation at the peak of 2009 giant outburst (see Section 2 and Table 1) was also analysed and presented in Fig. 2. The NuSTAR observation of the pulsar was performed at a higher flux level (≈5.14 × 10$^{-9}$ erg cm$^{-2}$ s$^{-1}$ in 3–30 keV range) as compared to the RXTE observation (≈4.13 × 10$^{-9}$ erg cm$^{-2}$ s$^{-1}$ in 3–30 keV range; see Section 4 for detailed spectral analysis). Irrespective of the flux difference, well agreement between the two profiles was observed except for the appearance of an additional dip in 0.7–0.8 phase range of the pulse profile observed from the NuSTAR data. Barycentric correction was then applied on the background subtracted light curves. The $\chi^2$-maximization technique (Leahy 1987) was utilized to estimate the spin period of the pulsar. Pulsations at a period of 17.475(6) s were detected in the source light curve. We also estimated the pulse period of the pulsar as 17.47(5) s, from the simultaneous Swift/XRT observation of the pulsar (see Section 2.2 for reduction procedures). The error on pulse period is estimated by fitting a Gaussian function on the chi-squared versus period distribution and is quoted for 1$\sigma$ level.

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### Table 1. Log of observations of 2S 1417−624 used in the present work.

| Satellite/Instrument | ObsID          | Start time (MJD) | Exposure (ks) | Pulse period (s) |
|----------------------|----------------|-----------------|---------------|-----------------|
| NuSTAR/FPMs          | 90402318002    | 58240.57        | 28.8,29.1$^a$ | 17.475(6)       |
| Swift/XRT            | 000888676001   | 58240.81        | 1.8           | 17.47(5)        |
| RXTE/PCA             | 94032-02-04-01 | 55158.21        | 3.4$^b$       | 17.502(9)       |

**Notes:** $^a$For FPMA and FPMB respectively. $^b$See Sections 2 and 3 in the text.

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1.http://www.swift.ac.uk/analysis/xrt/

2.http://starlink.eao.hawaii.edu/starlink
through phase-averaged and phase-resolved spectral studies (see Section 4).

We investigated the energy dependence of the pulse profiles of the pulsar by folding the energy resolved light curves obtained from the NuSTAR and Swift observations. This was done in order to understand the evolution of individual peaks and the emission geometry of the pulsar with energy. From Fig. 3, it is clear that the pulse profiles are strongly dependent upon the photon energy. Four peaks in the pulse profiles are visible up to $\approx 15$ keV along with the change in relative intensities of the individual peaks. The evolution of first peak in 0.0–0.2 phase range is found to be different as compared to other peaks in the sense that it gets narrower and prominent with increasing energy. The hard X-ray pulse profile (50–79 keV range) was found to be comparatively simple and appeared double peaked as the intensities of other peaks are reduced at higher energies. This is possibly due to the broadening of the minima (dip) after the first peak with increasing energy. The pulsations were detected in the light curves up to 79 keV. We notice a remarkable similarity in the evolution of the pulse profiles of the pulsar during the 2018 NuSTAR observation and the RXTE observations during 2009 outburst (Gupta et al. 2018), suggesting a similar accretion geometry during these outbursts.

Furthermore, we estimated the pulse fraction of the pulsar for the NuSTAR observation. Although, NuSTAR is operational in 3–79 keV energy range, we have estimated the value of pulse fraction in 3–60 keV energy band. This was done, in order to have a direct comparison with the previous outburst studies in 2009 (Gupta et al. 2018). The pulse fraction is defined as the ratio between the difference of maximum and minimum intensities to the sum of maximum and minimum intensities in the folded light curve. The pulse fraction in 3–60 keV range for the NuSTAR observation was estimated to be $23.4 \pm 0.4\%$ and is shown in Fig. 4. The estimated value of pulsed fraction seems to follow the negative correlation trend with the pulsar luminosity as observed during the previous 2009 outburst. Apart from the dependence of the pulsed fraction on luminosity, we have also studied the change in pulse fraction with energy (Fig. 5). It is evident that the pulsed fraction of 2S 1417–624 increases with energy, similar to other X-ray pulsars (Lutovinov & Tsygankov 2009).

Energy dependence of the pulsed fraction has been studied extensively for a large sample of transient Be/XBPs by Lutovinov & Tsygankov (2009). Most of the pulsars were found to exhibit a monotonic increase in the pulsed fraction with energy. While some of them additionally showed local features near the cyclotron line energy and its harmonics. The presence of these features was attributed to the effect of resonance absorption. This qualitative explanation for the increase in pulsed fraction with energy, is based on a simple geometrical model for the neutron stars with dipole magnetic fields (see Lutovinov & Tsygankov 2009, and references therein).

4 SPECTRAL ANALYSIS

4.1 Phase-averaged spectroscopy of 2S 1417–624

We performed phase-averaged spectroscopy of 2S 1417–624 in 0.9–79 keV energy range using simultaneous observations of the pulsar with NuSTAR and Swift/XRT, at the peak of the 2018 May giant outburst. The source and background spectra were accumulated by following the standard procedures described in Section 2. Using appropriate background, response matrices and effective area files, spectral fitting was carried out by XSPEC version 12.8.2 package. For simultaneous spectral fitting, all model parameters were tied together for FPMA, FPMB, and XRT spectra while the relative instrument normalizations were kept free. The cross-normalization...
The broad-band continuum spectrum of 2S 1417−624 has been described with a PL model modified with a cut-off at higher energies. Therefore, we initially approximated the spectrum with a cut-off PL model. Additionally, we detected a fluorescent iron emission line at 6.4 keV. The result of this fitting i.e., phabs*(CutoffPL + ga), yielded a reduced $\chi^2$ value of $>2$ and the corresponding residuals are shown in Fig. 6b. The presence of wave-like residuals in 1−15 keV energy range of the spectrum and high value of reduced $\chi^2$ made the fitting unacceptable. In order to account for these residuals, we included a thermal BB component with a temperature of $\sim$1 keV. Addition of this BB component improved the fitting with corresponding reduced $\chi^2$ value of $\approx$1.1 (Fig. 6c). We have also attempted to use partial covering (PC) absorber instead of the BB component, with a comparable statistical significance. Though the pulsar was observed at the highest luminosity till date (at the peak of 2018 giant X-ray outburst), there was no signature of presence of any cyclotron resonance scattering feature in the pulsar spectrum in 0.9−79 keV range.

We investigated several other standard continuum models such as HECut PL (White et al. 1983), a HECut PL with a smoothing Gaussian at cut-off energy (NewHcut; Burderi et al. 2000; Jaisawal & Naik 2015) and negative and positive exponential cut-off models, in order find a suitable continuum for 2S 1417−624. For all considered models, the addition of BB or a PC component and an iron line at $\sim$6.4 keV was necessary for the spectral fitting. The spectral parameters obtained from fitting the broad-band spectrum of the pulsar with these models are listed in Table 2. The value of equivalent hydrogen column density obtained from fitting various spectral models, was found to be in range $\approx$0.6−0.9 × 10$^{22}$ cm$^{-2}$ units, which is lower than the value of Galactic absorption in the source direction ($\approx$1.4 × 10$^{22}$ cm$^{-2}$; Willingale et al. 2013). This indicated that the presence of an additional absorber close to the neutron star is unlikely. However, the spectral fitting with PC model leads to significantly higher additional column density of $\approx$168 × 10$^{22}$ atoms cm$^{-2}$ units. Therefore, we consider the two-component model, i.e, CutoffPL and a thermal BB (CutoffPL+BB)
contribution of BB component, are shown in panels (b) and (c) of 79 keV energy range, obtained from to be the best-fitting continuum model. Panel (a) of Fig. 6 shows Figure 6. (a) Broad-band continuum spectrum of 2S 1417–624 in 0.9–79 keV energy range, obtained from Swift/XRT (blue), NuSTAR-FPMA (red), and -FPMB (black) detectors. The top panel shows the source spectra obtained from above-mentioned detectors along with the best-fitted model comprising of a cut-off PL continuum model and a BB component (Cutoff+BB) modified with the interstellar absorption and a Gaussian function for the iron emission line at 6.4 keV. Panels (b) and (c) show the spectral residuals obtained after fitting the broad-band spectrum, without and with the inclusion of BB component, respectively.

to be the best-fitting continuum model. Panel (a) of Fig. 6 shows the spectral fitting of 2S 1417–624 by CutoffPL+BB model. The residuals obtained by fitting the model without and with the contribution of BB component, are shown in panels (b) and (c) of Fig. 6, respectively.

4.2 Broad-band continuum modelling with physical models

The formation of accretion column above the magnetic poles of the accreting neutron star, is responsible to shape the characteristic spectrum of the X-ray pulsars (Becker & Wolff 2007). The detection of the thermal BB component in the phase-averaged spectrum of 2S 1417–624 motivated us to explore the properties of accretion column via physically motivated models such as BWmod (Becker & Wolff 2007) and COMPMAG model (Farinelli et al. 2012).

BWmod solves the radiative transfer equation (RTE) inside the accretion column analytically and it uses a specific velocity profile that is linearly dependent on optical depth of the column (Becker & Wolff 2007). It has been implemented on the bright pulsars such as 4U 0115+63, Her X−1 and EXO 2030+375 (Ferrigno et al. 2009; Wolff et al. 2016; Epili et al. 2017). Due to large uncertainty in the distance estimates for 2S 1417–624, we tried to use BWmod by considering two different distance values i.e. 5 and 11 kpc. However, our attempts to use BWmod to fit the pulsar spectrum failed with the reduced χ² value obtained from the fitting as >2 in each case.

Afterwards, we attempted to implement the COMPMAG model to the pulsar spectrum. COMPMAG model solves the RTE numerically and it offers different velocity profiles, characterized by an index η and a terminal velocity β. The other free parameters of the model are (i) temperature of seed BB spectrum kT0, (ii) electron plasma temperature kTe, and (iii) vertical optical depth of the accretion column τ. While fitting this model, we assumed the velocity profile of the accretion column to be linearly dependent on the optical depth (βτ ∝ τ, i.e. beta flag 2; Farinelli et al. 2012). This gives rise to an acceptable fit with reasonable values of spectral parameters (listed in Table 2). However, we also remark that this model is better suited for lower luminosity observations where the accretion flow is expected to get halted by Coulomb interactions, as opposed to a radiation-dominated shock expected in case of higher luminosities.

4.3 Pulse phase-resolved spectroscopy

In order to investigate the cause of four peaks in the pulse profiles, the nature of thermal BB component and the variation of other spectral parameters during the 2018 May outburst, we carried out pulse phase-resolved spectroscopy of 2S 1417–624 by using NuSTAR observation. For this, the source spectra were accumulated in 10 phase bins by applying phase filters on the barycentric corrected event file in XSELECT package. For phase-resolved spectral fitting, we used the same energy range as chosen for the phase averaged spectroscopy of the NuSTAR data. Each individual phase-sliced spectra were fitted by using appropriate background, response, and effective area files. As in case of phase averaged spectral fitting, both the cutoff+BB and HECut+BB models along with the photoelectric absorption component and a Gaussian function at 6.4 keV were used to fit the spectra of each phase bins. It was found that both the models fit all the phase-resolved spectra well, yielding comparable values of fitted parameters. While fitting, the value of equivalent hydrogen column density was fixed to the phase-averaged value (NHI; Table 2). The phase-resolved spectral parameters obtained from the fitting are shown in Fig. 7 for cutoff+BB model, along with the pulse profile of the pulsar at the top panel.

Although the shape of the pulse profile of 2S 1417–624 during NuSTAR observation was significantly different from those during previous outbursts in RXTE era, the variation in the spectral parameters over the pulse phases were marginal. From Fig. 7, it can be seen that the values of PL photon index and cut-off energy were found to be variable in range −0.1 to 0.3 and 13–17 keV, respectively. The BB component was detectable in all phase bins except for one (fourth panel of Fig. 7), which indicates that the BB flux was either too low or not significant beyond 3 keV. While the BB temperature was found to be almost constant (within errors) throughout the pulse phases. The PL and model fluxes obtained in 3.5–79 keV energy range, from the fitting of individual phase bins, follow the shape of pulse profiles (fifth and seventh panels of Fig. 7, respectively). Apart from the shape of total flux profiles over the pulse phase, an enhancement in the BB flux component could be clearly seen in 0.1–0.2, 0.4–0.5, and 0.9–1.0 phase ranges (sixth panel; Fig. 7). This enhanced value of BB flux can be associated with the peculiar evolution of peaks in the energy resolved pulse profiles (Fig. 3). All the flux values quoted in the paper are calculated by using the efold×convolution model. Other parameters such as iron line energy and its equivalent width were found to be consistent with the phase-averaged values and do not show any significant variation over the pulse phase.
Table 2. Best-fitting spectral parameters (90 per cent errors) obtained from the simultaneous NuSTAR and Swift/XRT observations of 2S 1417–624. The fitted models are (i) HECut PL with a BB component, (ii) cut-off PL model with BB, (iii) NEWHCUT model with a BB component, (iv) cut-off PL modified with a PC absorption, and (v) COMPMAG model along with photoelectric absorption component and a Gaussian component for iron emission line.

| Parameters | HECut+BB | Cutoff+BB | Spectral models | CutoffPL(with PC) | COMPMAG |
|------------|----------|-----------|-----------------|-------------------|---------|
| $N_{H}^{a}$ | 0.63 ± 0.05 | 0.72 ± 0.04 | 0.69 ± 0.04 | 0.83 ± 0.04 | 0.67 ± 0.06 |
| $N_{H}^{b}$ | – | – | – | 168.3 ± 12.4 | – |
| Covering fraction | – | – | – | 0.16 ± 0.01 | – |
| Photon index | 0.12 ± 0.01 | 0.12 ± 0.01 | 0.10 ± 0.01 | 0.37 ± 0.01 | – |
| $E_{bb}$ (keV) | 3.1 ± 0.5 | 15.3 ± 0.2 | 5.4 ± 0.4 | 17.04 ± 0.15 | – |
| $E_{bb}$ (keV) | 15.3 ± 0.1 | – | 5.2 ± 0.2 | – | – |
| BB temperature (keV) | 0.94 ± 0.04 | 0.96 ± 0.04 | 0.94 ± 0.03 | – | – |
| COMPMAG $kT_{bb}$ (keV) | – | – | – | 0.86 ± 0.06 | – |
| COMPMAG $kT_{bb}$ (keV) | – | – | – | 4.45 ± 0.12 | – |
| COMPMAG $\tau$ | – | – | – | 0.90 ± 0.02 | – |
| Column radius (km) | – | – | – | 2.18 ± 0.05 | – |

Iron line parameters

| Component flux (1–79 keV) $^{c}$ | PL flux | BB flux |
|----------------------------------|---------|---------|
| 8.11 ± 0.02 | 8.11 ± 0.01 | 0.13 ± 0.01 |
| 8.11 ± 0.02 | 8.09 ± 0.03 | 0.13 ± 0.01 |
| 8.24 ± 0.03 | 0.15 ± 0.02 | – |

Source flux $^{c}$

| Flux (1–10 keV) | Flux (10–79 keV) | Reduced $\chi^2$ (d.o.f.) |
|----------------|----------------|--------------------------|
| 1.46 ± 0.02 | 6.78 ± 0.01 | 1.10 (1065) |
| 1.47 ± 0.01 | 6.77 ± 0.02 | 1.10 (1066) |
| 1.47 ± 0.01 | 6.78 ± 0.01 | 1.10 (1065) |
| 1.46 ± 0.01 | 6.79 ± 0.01 | 1.11 (1064) |
| 1.47 ± 0.02 | 6.80 ± 0.02 | 1.11 (1066) |

Notes: $^{a}$ Equivalent hydrogen column density in the source direction (in 10$^{22}$ atoms cm$^{-2}$ unit).
$^{b}$ Additional hydrogen column density (in 10$^{22}$ atoms cm$^{-2}$ unit).
$^{c}$ Unabsorbed flux in unit of 10$^{-9}$ erg cm$^{-2}$ s$^{-1}$.

5 DISCUSSION AND CONCLUSIONS

In the present work, we have performed timing and spectral analysis of 2S 1417–624 during its 2018 giant outburst by using simultaneous observations with the NuSTAR and Swift observatories. These observations were performed at a flux level of approximately 350 mCrab (i.e. at the peak of the giant outburst) as recorded in Swift/BAT (Nakajima et al. 2018). It is one of the brightest giant X-ray outburst observed from the source till date. One of the most interesting aspect of the present study is the featuring of four peaks in the pulse profile of the pulsar which have never been observed before, during any type of outburst from 2S 1417–624. Our results are in agreement with the previous findings that the pulse profiles of the pulsar are strongly luminosity dependent (Gupta et al. 2018). These pulse profiles were found to be strongly dependent upon photon energy as well (see Fig. 3).

The transient Be/XBPs are known to show multiple dips and peaks in their pulse profiles during X-ray outbursts. These peaks are known to be strongly energy dependent in nature. A few of such pulsars showing energy and luminosity dependence of pulse profiles are EXO 2030+375 (Naik et al. 2013; Epili et al. 2017), GX 304–1 (Jaisawal, Naik & Epili 2016), A0535+26 (Naik et al. 2008), and 1A 1118–61 (Maitra et al. 2012). Pulse phase-resolved spectroscopy of observations of these pulsars during outbursts revealed the presence of additional matter at the dip phases in the pulse profiles. This suggest that the dips or dip-like features in pulse profiles are due to the absorption/obscuration of X-ray photons by additional local matter present around the neutron stars. Following this, we modelled the phase-resolved spectra of 2S 1417–624 with a PC cut-off PL model. As described in Section 4.3, we fixed the value of equivalent hydrogen column density ($N_{H}$) to the phase-averaged value and left additional hydrogen column density ($N_{H_2}$) free to vary. We obtained an exceptionally high value of additional column density during the primary dip (0.95–1.05 pulse phase range: top panel of Fig. 7). During other phases, there was no significant variation in the additional column density to draw any conclusion on this regard. Future studies with sensitive soft X-ray instruments like NICER could provide conclusive results on the matter distribution around the poles of the neutron star.

2S 1417–624 is a unique pulsar in the sense that it shows highly luminosity dependent pulse profiles, ranging from a single broad peak at low luminosities to multiple (four) peaks at higher luminosities (Gupta et al. 2018 and present work). A detailed pulse profile modelling is required to study this diverse behaviour of the source. However, such a study requires a physically motivated self-consistent working model to explain the pulsar beam geometry which takes into account of the beam pattern and gravitational light bending effects, which is extremely complex and outside the scope of this paper.

Despite the complexity of pulsar emission mechanism, the broadband spectrum of 2S 1417–624 has been successfully described with the standard continuum models such as cut-off PL and HECut PL models (Inam et al. 2004; Gupta et al. 2018, and references therein). However, in the present study, we found that these models are not suitable to describe the spectrum obtained at the peak of the 2018 giant X-ray outburst. Rather, it was found that a composite model consisting of a cut-off PL and BB component was required to describe the spectrum well. The NuSTAR observation presented...
Here was carried out when the pulsar was brighter compared to the RXTE observations during the 2009 giant X-ray outburst. The additional BB component is, therefore, very likely due to the enhanced luminosity of the pulsar though, the sensitivities of NuSTAR detectors at soft X-ray ranges are better than the RXTE/PCA.

Several of the accretion powered XBP have been observed to show an excess in the soft X-ray ranges of their spectrum. This is known as soft excess and has been modelled with an additional thermal component in the pulsar spectrum. This soft excess is thought to be a very common intrinsic feature of XBP. However, its detectability depends upon the source flux and column density ($N_H$) in the source direction (see Hickox et al. 2004 for a review). The possible mechanism behind the origin of this component could be: (i) emission from accretion column, (ii) thermal emission from collisionally energized diffuse gas around the neutron star, (iii) reprocessing of hard X-rays by diffuse cloud, and (iv) reprocessing of hard X-rays in optically thick accretion disc (Hickox et al. 2004). By using the value of BB normalization obtained from the phase-averaged spectral fitting and considering the source distance of 5 kpc, the radius of BB emitting region is estimated to be $\sim$2 km. In our study, the presence of hard Comptonized spectrum as well as an emitting radius of $\sim$2 km makes difficult to consider accretion column as a primary source of soft excess emission. The non-pulsating nature of BB component also suggests the same. Alternatively, it is possible that the neutron star surface is contributing for reflection of X-ray photons from the column. This may explain the presence of non-pulsating thermal emission from the pulsar. A similar analogy is suggested by Poutanen et al. (2013) on cyclotron line scattering feature.

In the present study, we have witnessed a change in spectral continuum at higher luminosity. By considering a distance of 5 and 11 kpc, the source luminosity in 1–79 keV range was estimated to be $\sim$2.46 $\times$ 10$^{37}$ and 1.19 $\times$ 10$^{38}$ erg s$^{-1}$, respectively. This luminosity ($\sim$10$^{39}$ erg s$^{-1}$) is crucial in understanding the accretion state transitions in accretion powered X-ray pulsars and is known as critical luminosity (Becker et al. 2012). At such high luminosities, the radiation-dominated shocks may form near the neutron star surface, giving rise to dramatic changes in pulsar beam configuration and spectral parameters (see Reig & Nespoli 2013; Epilii et al. 2017). Thus, the spectral changes seen in the present study could be associated with the critical luminosity of the source. Similar results were found during the previous giant outburst in 2009 when the pulsed fraction of the pulsar was anticorrelated with the source flux in a luminous regime (Gupta et al. 2018).

It is also important to note that a positive correlation was detected between pulsed fraction and flux below 1.2 $\times$ 10$^{-9}$ erg cm$^{-2}$ s$^{-1}$ (see fig. 2 of Inam et al. 2004). Above this limit, we detected a clear anticorrelation in the present study. The observed anticorrelation can be attributed to the increase in unpulsed component from the pulsar in the form of fan beam emission close to the critical luminosity. The timing analysis, in the present study (Fig. 4) also supports this idea in context of earlier finding by Gupta et al. (2018).

In summary, we have presented a detailed spectral and timing analysis of 2S 1417–624 during the 2018 giant outburst by using simultaneous observations from NuSTAR and Swift observatories. The pulse profiles were found to four-peaked and strongly dependent on energy. The broad-band energy spectrum of the pulsar is well described with a composite spectrum consisting of cut-off PL and a thermal BB component along with an iron fluorescence line at $\sim$6.4 keV. Considering the source distance to be $\sim$5 kpc, we estimated the radius of the BB emitting region to be $\sim$2 km. The reflection of X-ray photons from the stellar surface possibly contributes to the observed soft excess. Based on the results obtained from spectral fitting via physical and empirical models, we interpret that the source is consistently accreting close to the critical luminosity regimes.

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**Figure 7.** Spectral parameters obtained from the phase-resolved spectroscopy of 2S 1417–624 during NuSTAR observation in 2018 May by using cutoff+BB continuum model. Top panel shows the pulse profile of the pulsar in 3–79 keV energy range. The values of PL photon index, cut-off energy ($E_{cut}$) and BB temperature are shown in the second, third and fourth panels from top respectively. The PL flux, BB component flux and total flux in 3.5–79 keV range are presented in fifth, sixth and seventh panels respectively. All fluxes are quoted in the units of 10$^{-9}$ erg cm$^{-2}$ s$^{-1}$. The errors in the spectral parameters are estimated for 90 per cent confidence level.
REFERENCES

Apparao K. M. V., Naranan S., Kelley R. L., Bradt H. V., 1980, A&A, 89, 249
Basko M. M., Sunyaev R. A., 1976, MNRAS, 175, 395
Becker P. A. et al., 2012, A&A, 544, A123
Becker P. A., Wolff M. T., 2007, ApJ, 654, 435
Bellm E. C. et al., 2014, ApJ, 792, 108
Boldin P. A., Tsygankov S. S., Lutovinov A. A., 2013, Astron. Lett., 39, 375
Burderi L., Di Salvo T., Robba N. R., La Barbera A., Guainazzi M., 2000, ApJ, 530, 429
Burrows D. N. et al., 2005, Space Sci. Rev., 120, 165
Currie M. J., Berry D. S., Jenness T., Gibb A. G., Bell G. S., Draper P. W., 2014, in ASP Conf. Ser. Vol. 485. Astron. Soc. Pac., San Francisco, p. 391
Doroshenko V., Tsygankov S. S., Mushotkov A. A., Lutovinov A. A., Santangelo A., Suleimanov V. F., Poutanen J., 2017, MNRAS, 466, 2143
Epili P., Naik S., Jaisawal G. K., Gupta S., 2017, MNRAS, 472, 3455
Farinelli R., Ceccobello C., Romano P., Titarchuk L., 2012, A&A, 538, 67
Ferrigno C., Becker P. A., Segreto A., Mineo T., Santangelo A., 2009, A&A, 498, 825
Finger M. H., Wilson R. B., Chakrabarty D., 1996, A&AS, 120, 209
Forman W., Jones C., Cominsky L., Julien P., Murray S., Peters G., Tananbaum H., Giacconi R., 1978, ApJS, 38, 357
Grindlay J. E., Petro L. D., McClintock J. E., 1984, ApJ, 276, 621
Gupta S., Naik S., Jaisawal G. K., Epili P., 2018, MNRAS, 479, 5612
Harrison F. A. et al., 2013, ApJ, 770, 103
Hickox R. C., Narayan R., 2004, ApJ, 614, 881
Horne J. H., Baliunas S. L., 1986, ApJ, 302, 757
Inam S. C¸., Baykal A., Matthew Scott D., Finger M., Swank J., 2004, MNRAS, 349, 173
Jahoda K., Swank J. H., Giles A. B., Stark M. J., Strohmayer T., Zhang W., Morgan E. H., 1996, in Siegmund O. H., Gummin M. A., eds, Proc. SPIE, Vol. 2808, EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy VII. SPIE, Bellingham, p. 59
Jaisawal G. K., Naik S., 2015, MNRAS, 448, 620
Jaisawal G. K., Naik S., Epili P., 2016, MNRAS, 457, 2749
Kelley R. L., Dossey R. E., Jernigan J. G., Rappaport S., Apparao K. M. V., Naranan S., 1981, ApJ, 243, 251
Krimm H. A. et al., 2009, Astron. Telegram, 2276
Krimm H. A. et al., 2013, ApJS, 209, 14
Krimm H. A. et al., 2018, Astron. Telegram, 11569
Kühnel M. et al., 2017, A&A, 607, 88
Leahy D. A., 1987, A&A, 180, 275
Lomb N. R., 1976, ApSS, 39, 447
Lutovinov A. S., Tsygankov S. S., 2009, Astron. Lett., 35, 433
Maitra C., Paul B., Naik S., 2012, MNRAS, 420, 2307
Markert T. H. et al., 1979, ApJS, 39, 573
Mushotkov A. A., Suleimanov V. F., Tsygankov S. S., Poutanen J., 2015, MNRAS, 447, 1847
Naik S. et al., 2008, ApJ, 672, 516
Naik S., Maitra C., Jaisawal G. K., Paul B., 2013, ApJ, 764, 158
Nakajima M. et al., 2018, Astron. Telegram, 11479
Paul B., Naik S., 2011, Bull. Astron. Soc. India, 39, 429
Poutanen J., Mushotkov A. A., Suleimanov V. F., Tsygankov S. S., Nagirner D. I., Doroshenko V., Lutovinov A. A., 2013, ApJ, 777, 115
Reig P., 2011, Ap&SS, 332, 1
Reig P., Nespoli E., 2013, A&A, 551, A1
Raicher H., Paul B., 2010, MNRAS, 406, 2663
Roberts D. H., Lehar J., Dreher J. W., 1987, AJ, 93, 968
Scargle J. D., 1982, ApJ, 263, 835
Tsygankov S. S., Wijnands R., Lutovinov A. A., Degenaar N., Poutanen J., 2017a, MNRAS, 470, 126
Tsygankov S. S., Mushotkov A. A., Suleimanov V. F., Doroshenko V., Abolmasov P. K., Lutovinov A. A., Poutanen J., 2017b, A&A, 608, A17
Wilson-Hodge C. A. et al., 2018, ApJ, 863, 9
White N. E., Swank J. H., Holt S. S., 1983, ApJ, 270, 711
Willingale R., Starling R. L. C., Beardmore A. P., Tanvir N. R., O’Brien P. T., 2013, MNRAS, 431, 394
Wolff M. T. et al., 2016, ApJ, 831, 194

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