ULX pulsar Swift J0243.6+6124 observations with NuSTAR– dominance of reflected emission in the super-Eddington state

S.D. Bykov$^{1,2,*}$, M.R. Gilfanov$^{1,3}$, S.S. Tsygankov$^{4,3}$ and E.V. Filippova$^3$

$^1$Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str 1, Garching b. München D-85741, Germany
$^2$Kazan Federal University, 18 Krelyovskaya street, Kazan, Russia
$^3$Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, 117997 Moscow, Russia
$^4$Department of Physics and Astronomy, FI-20014 University of Turku, Finland

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We report the discovery of the bright reflected emission component in the super-Eddington state of the ULX pulsar Swift J0243.6+6124, based on the NuSTAR observations of the source during its 2017 outburst. The flux of the reflected emission is weakly variable over the pulsar phase while the direct emission shows significantly larger pulsation amplitude. We propose that in this system the neutron star finds itself in the centre of the well formed by the inner edge of the geometrically thick super-Eddington accretion disc truncated by the magnetic field of the pulsar. The aspect ratio of the well is $H/R \sim 1$. The inner edge of the truncated disc is continuously illuminated by the emission of the accretion column giving rise to the weakly variable reflected emission. As the neutron star rotates, its emission sweeps through the line of sight, giving rise to the pulsating direct emission. From Doppler broadening of the iron line, we measure the truncation radius of the accretion disc $\sim 50 R_g$. The inferred dipole component of the magnetic field is consistent with previous estimates favouring a not very strong field. The uniqueness of this system is determined by its moderately super-Eddington accretion rate and the moderate magnetic field so that the inner edge of the truncated geometrically thick accretion disc is seen from the neutron star at a large solid angle.

Key words: pulsars: individual: Swift J0243.6+6124 –X-rays: binaries

1 INTRODUCTION

The X-ray transient Swift J0243.6+6124 was discovered by Swift observatory during its 2017 outburst (Cenko et al. 2017). Pulsations with a 9.8 sec period were detected (Kennea et al. 2017), establishing the source as an accreting neutron star and a transient X-ray pulsar (XRP). The outburst lasted ~ 200 days, after which the source transitioned to the regime of flaring activity. The optical counterpart was found to be a Be star (Kouroubatzakis et al. 2017; Reig et al. 2020) confirming that the source belongs to the class of Be X-ray binaries (BeXRB). From Gaia data, the distance to the source was estimated to be $6.8^{+1.5}_{-1.1}$ kpc (Bailer-Jones et al. 2018); the mean value of the distance value is adopted below. At the peak of the outburst, the source reached the luminosity of $\sim 2 \cdot 10^{39}$ erg s$^{-1}$ (bolometric) which exceeds the Eddington limit for a neutron star by a factor of ~ 10 (Tsygankov et al. 2018; Doroshenko et al. 2020), thus placing the source in a cohort of Ultra-Luminous X-ray pulsars (ULX pulsars). Remarkably, it is the first of this kind found in our galaxy.

Due to its uniqueness, X-ray studies of Swift J0243.6+6124 are plentiful. Wilson-Hodge et al. (2018) investigated the spectral and timing behaviour of the pulsar with Fermi/GBM and NICER telescopes. They found that the pulse profile shows strong evolution and energy dependence, with a transition from single- to double-peaked shape (and vice-versa) as the pulsar brightens (fades). Such behaviour is typical for transient X-ray pulsars and has been predicted theoretically (Basko & Sunyaev 1975). From the luminosity at which the pulse profile change happens they estimated the magnetic field of the neutron star to be $B > 10^{13}$ G. However, based on the absence of the propellor effect at the declining phase of the outburst, Tsygankov et al. (2018); Doroshenko et al. (2020) argued that the magnetic field should be smaller. Kong et al. (2022) reported the discovery of the variable cyclotron scattering absorption feature (CSRF) in the spectrum of this pulsar (in the energy range 120–140 keV). The implied magnetic field strengths is therefore $\sim 1.6 \times 10^{13}$ G, and it is believed to originate from the non-dipole component of the magnetic field.

Insight-HXMT provided broadband X-ray data with high cadence (Zhang et al. 2019; Kong et al. 2020; Wang et al. 2020). Using these data Doroshenko et al. (2020) reported specific changes in timing and spectral properties of the pulsar. These changes were interpreted as an onset of super-Eddington accretion via the gas pressure dominated disc and the following transition to the radiation pressure supported disc (RPD). These results are important since they show that not only do radiation patterns change with pulsar luminosity, but also surrounding matter distribution may evolve in the course of the outburst. The presence of the RPD indicates that the magnetic field may not be very large. This claim is furtherly substantiated by the presence of pulsations and variability of X-ray flux in a quiescent state observed by NuSTAR (Doroshenko et al. 2020).

* E-mail: sergei.d.bykov@gmail.com

© 2022 The Authors
The iron line complex was studied extensively by Jaisawal et al. (2019) using NICER and NuSTAR data. They detected several bright lines of asymmetric shape in the 6 – 7 keV range. In particular, data could be fitted with the model consisting of lines at 6.4, 6.7 and 6.98 keV from neutral and ionized iron species. In their model, the 6.4 keV line was very broad (σ up to 1 keV). They interpreted these results that the iron emission is produced in the accretion disc or plasma trapper in the magnetosphere. Tao et al. (2019) also reported the presence of the significant reflection component and relativistic line shapes in Swift J0243.6+6124.

The peak luminosity of Swift J0243.6+6124 lies between ‘normal’ transient XRP and bright ULX pulsars. Significant changes in the line shapes in Swift J0243.6+6124.

Notwithstanding ample observational data, only one phase-resolved spectroscopic study was done with NuSTAR data in the sub-Eddington state of the pulsar (Jaisawal et al. 2018). This paper aims to fill this gap and is dedicated to the phase-resolved spectroscopy of NuSTAR data in the high luminosity state, with particular emphasis on the behaviour of the iron line complex. In section 2 we describe the data reduction and analysis. In sect. 3.1 we discuss the timing analysis, in 3.2 we describe the results of phase-averaged spectra, and in 3.3 we report on the phase-resolved spectroscopy. We discuss our results in sect. 4 and conclude in sect. 5.

2 NuSTAR DATA

NuSTAR (Harrison et al. 2013) is a grazing incidence hard X-ray telescope sensitive in the 3–79 keV energy range with the energy resolution of 4% at 10 keV. It consists of two identical modules: FPMA and FPMB, data from each being processed separately. In the course of its 2017-2018 type II outburst, Swift J0243.6+6124 was observed with NuSTAR five times between MJD 58000 and MJD 58200, observations 90302319002(4,6,8) and 90401308001. Observation 90401308001 was excluded due to its short exposure. We add observation 90401308002 of one of the subsequent mini-outburst (likely Type I outburst) to our data set. We use the following aliases for observations: 90302319002 – I, 90302319004 – II, 90302319006 – III, 90302319008 – IV, 90401308002 – V. Dates of the observations are the following: I - MJD 58032; II - MJD 58057; III - MJD 58067; IV - MJD 58094; V - MJD 58369.

The NuSTAR data reduction was carried out using the HEASOFT v. 6.28 package and NuSTAR CALDB files (v117). Standard data-processing tools were used to extract level 2 (nupipeline) and 3 (nuproducts) products. We choose source and background regions for data extraction: the former is centered on the source position, while the latter is placed as far from the source as possible. Both regions have a circular shape with a 180 arcsec radius. Because of the high count rate in all observations we set a bitmask “STA-

3 RESULTS

Fig. 1 shows the long term light curve of the source in the 15–50 keV band (Swift/BAT data\(2\)) and the 0.3–10 keV range (Swift/XRT data\(3\)). The main, giant, outburst lasts approx 200 days and is followed by a series of smaller flares (possibly Type I outbursts). Dates of NuSTAR observations are marked with vertical lines. All NuSTAR spectra were grouped to have at least 25 counts per energy bin and \(\chi^2\) statistics was used. The error intervals are given for 90% confidence.

3.1 Timing analysis

Pulsations of X-ray flux are detected in all observations. For each observation, we determine the period of the pulsar with EFSEARCH routine, using combined data of both NuSTAR detectors. The periods are 9.85425, 9.84435, 9.82340, 9.80105, and 9.7918 seconds for observations I, IIII, III and IV respectively (Solar system barycenter). These values of periods were used for folding the data for pulse profiles.

In Fig. 2 we show the pulse profiles in the 4–79 keV energy range of all five NuSTAR observations. Pulse profiles are normalized to the mean count rate (per observation). At the beginning of the outburst (observation I), the pulse profile has a complex shape with multiple minor peaks, but overall the profile is dominated by the one-peak component. The last observation (V) taken during another, minor

---

1 https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/
2 https://swift.gsfc.nasa.gov/results/transients/weak/SwiftJ0243.6p6124/
3 reduced from an online tool https://www.swift.ac.uk/user_objects/, see (Evans et al. 2007)
flame, but in similar brightness, shows a very similar shape. The pulsed fraction $PF^4$ is ~ 30% in the considered energy range.

As the source becomes more luminous, the pulse profile changes drastically. In the two observations where the source was the brightest (II and III), the pulse profiles show a very smooth and symmetric double-peaked shape. In observation II the peaks are roughly equal in amplitude and the pulsed fraction is ~ 45%, whilst in observation III one peak dominates the overall shape and the pulsed fraction is somewhat larger, ~ 55%. In the next observation, IV, the pulse profile features two asymmetric peaks of roughly equal height. The pulsed fraction is ~ 30%. The dependence of $PF$ on the energy of photons may be found in Tao et al. (2019) or Wang et al. (2020). Note that as we did not do phase-connection between individual observations, Fig. 2 may not correctly represent how a particular pulse profile maximum evolves in time, but rather shows the general evolution of the shape of the pulse profile (see Doroshenko et al. 2020; Jiren et al. 2022).

### 3.2 Phase-average spectral analysis

The X-ray spectra of Swift J0243.6+6124 measured by various observatories have been extensively analysed in the works cited in section 1 and the main parameters for common pulsar spectral models have been obtained and discussed. Below we focus on several facts and features, which were not considered in the previous analyses.

A remarkable feature of the spectrum of Swift J0243.6+6124 in the super-Eddington state (observations II, III, IV, the 4–79 keV luminosity of the order of ~ $10^{39}$ erg s$^{-1}$) is the presence of strong reflection features, most notably of the fluorescent line of iron. This is illustrated by Fig. 3 where the ratio of the NuSTAR spectra to a simple power-law model with photon index $\Gamma = 2$ are shown. For these observations, an approximation of the spectrum with the power-law with an exponential cutoff continuum with a superimposed Gaussian line gives the equivalent width of the line 0.9 ± 0.05 keV for the brightest observation. Also quite obvious in the ratio plot are a smeared absorption edge in the ~ 7 – 15 keV range and a possible Compton reflection hump at the ~ 15 – 30 keV energy domain. All these features are familiar signatures of the reflected emission complicated by photo-ionization effects and, possibly, by relativistic smearing (Ross & Fabian 2005).

On the contrary, in the sub-Eddington state (observations I and V) where the source luminosity was ~ few $\times 10^{37}$ erg s$^{-1}$ these features are much less pronounced (Fig. 3). Indeed, the equivalent width of the Gaussian line in these observations was 90 ± 5 eV, close to typical values for X-ray binaries in the hard spectral state. During these observations, the source spectrum was quite close to a typical spectrum of an accreting X-ray pulsar (Jaisawal et al. 2018).

In observation IV the source was at the declining part of the light curve (Fig.1) and its luminosity was the lowest among the three super-Eddington state observations, $L_X \sim 4 \cdot 10^{38}$ erg s$^{-1}$. Interestingly, in this observation, the equivalent width of the iron line is large, 0.83 ± 0.02 keV, however, the shape of the continuum is close to sub-Eddington state spectra found in observations I and V (lower panel in Fig. 3). It appears that this observation caught the source in transition from super-Eddington to the sub-Eddington state.

Motivated by the ratio plot in Fig. 3 we use the following spectral model to describe the emission of the Swift J0243.6+6124 in the super-Eddington regime: phabs*(relxilllp+ bbodyrad). The

\[ \text{phabs} \left( \frac{C_{\text{min}}}{C} \right) \]

\[ \frac{C}{C_{\text{max}}} \]

\[ \text{of the pulse profile} \]

\[ PF = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}}} \]

\[ \text{defined as} \]

\[ \text{for readability.} \]
rexlilllp\(^5\) (García et al. 2014; Dauser et al. 2016) [v1.4.3] component models reflection of the the primary emission (a power law with exponential cutoff) from an accretion disc in lamp-post geometry, with account for possible photo-ionization of the disc material and relativistic smearing of the reflection spectrum. Previously, such a model, in its relxill variant, was successfully applied to the NICER+NuSTAR spectra of Swift J0243.6+6124 by Jaisawal et al. (2019). The multiplicative component phabs takes care for the interstellar absorption. The total Galactic absorption in the direction of the source has the column density of \(0.8 \times 10^{22} \text{ atoms cm}^{-2}\)\(^6\).

For the sake of fit stability, we fix phabs parameter at this value. The bbodyrad component accounts for thermal radiation reported in previous works.

For relxilllp, we use the following setup: spin of the object \(a\) and its redshift \(z\) are both set to 0; iron abundance \(A_{\text{Fe}}\) is set to 5.0 (Jaisawal et al. 2019); inner disc radius \(R_{\text{in}}\), power law index \(\Gamma\), cut-off energy \(E_{\text{cut}}\) and ionization parameter \(\log \xi\) are free parameters. Outer disc radius was set to 1.1 \(R_{\text{in}}\), this choice will be discussed later. Inclination is a free parameter. Height of the lamp-post source \(h\) is set to 5 \(R_{\text{g}}\) (five gravitational radii). Reflection factor \(f_{\text{refl}}\) controls the amplitude of the reflected component relative to the primary continuum and is a free parameter. \(f_{\text{refl}}\) is an analogue to the equivalent width of the iron line. The cross-calibration constant is added between FPMA and FPMB spectra. Table 1 shows the best-fitting values of parameters in observations II, III, and IV. Fig. 4 shows the spectral data and models. For observations I and V, when the source was in the sub-Eddington state, the spectra are adequately approximated by more simple standard pulsar models (Jaisawal et al. 2018) without the need for a significant reflection component. Therefore we focus our attention on the super-Eddington state spectra.

For the super-Eddington state, the reflection model gives fairly consistent values of parameters between three observations. The spectra in the super-Eddington state require large values of reflection fraction \(f_{\text{refl}} \sim 0.1 - 0.2\) which is not surprising, given the large values of the equivalent width of the iron line obtained in the simple Gaussian fits. Interestingly, the data require both relativistic smearing of the iron line as well as photo-ionization of the reflector’s material with a fairly large ionization parameter \(\log \xi \sim 3.5\) with a typical uncertainty 0.05. The inner radius of the disc \(R_{\text{in}} \sim 50 - 70 R_{\text{g}}\) corresponds to a circular velocity of approximately 10\% of the speed of light for a Keplerian disc. This explains the significant width of the 6.4 keV line reported earlier (Tao et al. 2019; Jaisawal et al. 2019) as well as the presence of the lines of He- and H-like iron. These findings are quite important and will be discussed in the context of the truncated thick disc picture in the following section. The best-fitting model consistently requires fairly low values of the inclination angle of \(\approx 10 - 20^\circ\) for all three observations with the errors in \(2 - 4^\circ\) range. However, it is worth noting that in the geometry proposed in this paper the inclination angle does not have the same straightforward meaning as in the geometry of a lamp post above an accretion disc envisaged in the relxilllp model. This is further discussed in Section 4.

As was noted above, in observation IV the source appeared to be in transition from super- to sub-Eddington state. This may explain the harder photon index and smaller reflection amplitude found in this observation (Table 1). However, the presence of the reflected component in this spectrum is required with high statistical confidence.

\(5\) http://www.sternwarte.uni-erlangen.de/~dauser/research/rexlill/

\(6\) https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl, see HI4PI Collaboration et al. (2016)

Figure 4. Unfolded spectra of the source and its model for observation II-IV. The top subplots show the unfolded spectra from FPMA (circles) and FPMB (squares) which are coloured according to the observation ID. A solid line represents the best-fitting approximation, whose components are also shown: reflection (dotted), power-law continuum (dashed), the thermal radiation (dash-dotted). The lower subplots show the respective residuals from the model. Spectral data were rebinned for plotting purposes.

Likewise, the relativistic broadening of the iron line, expressed in the value of \(R_{\text{in}}\), parameter, is similar to the other two super-Eddington observations.

Further insights into the geometry of the super-Eddington accretion flow around the magnetized neutron star are provided by the results of pulse phase-resolved spectroscopy.

3.3 Phase-resolved spectral analysis

Using the data of three NuSTAR observations of the source in the super-Eddington state, we study the evolution of spectral parameters as a function of the rotational phase of the neutron star. To this end, the pulse period is divided into 10 phase bins of equal width, and the spectra are extracted for each phase bin as described in section 2. We fit the spectra with the same model as for the phase-averaged case, except that we fix \(R_{\text{in}}\), \(\log \xi\), inclination angle, and parameters of the black body component at the values found for phase-averaged spectra. For all observations and in phase bins we obtained adequate
quality of the fit with the reduced $\chi^2$ in the $\chi^2$/dof $\sim 1.1$ range for a typical number of degrees of freedom $\sim 1100 \sim 1600$. The phase dependence of the best-fitting parameters is shown in Fig. A1, and the representative models in Fig. A2. The parameters value are presented in Table A1. Making log $\xi$ and parameters of the black body component free does not change significantly other parameters of the model and does not affect the interpretation of the results. For simplicity, we do not consider these more sophisticated fits further and focus on our main finding of the presence of a strong reflected component and its behaviour with the pulse phase.

Using the best-fitting model we compute the flux of reflected and direct emission for each spectrum. We do not compute the uncertainties in those values since it would require computationally-heavy calculations of the parameter chains which is unnecessary because the errors are sufficiently small for the purpose of this work. This is demonstrated by the high accuracy of $f_{\text{eff}}$ estimates as well as by the low level of noise in the obtained pulse profiles for the direct and reflected flux. Phase dependence of the direct and reflected flux as well as the total flux and reflection fraction $f_{\text{eff}}$ are shown in Fig. 5. An immediate conclusion from these plots is that the reflected component is much less variable with the pulse phase than the direct emission. As discussed in the next section, this can be understood in a picture of a rotating neutron star located in the middle of a geometrically thick super-Eddington accretion disc truncated by the magnetic field of the strongly magnetized neutron star. The pulsation amplitude$^7$ of the direct emission is $\sim 3.5, 5.0, 2.0$ in observations II, III and IV respectively, whereas for the reflected emission the numbers are, respectively, $\approx 1.5, 2.3, 1.3$. The pulsation amplitude for the reflected emission is $\sim 2 \sim 3$ times smaller than for the direct emission, which leads to the large pulsations in the reflected fraction $f_{\text{eff}}$.

Other parameters of the model show a complex pattern of variations with the pulse phase (Fig. A1). The spectral hardness and the cut-off energy seem to be slightly correlated with the total pulsar flux, as commonly observed in such objects (e.g. Tsygankov et al. 2017).

The results of the phase resolved spectral analysis are summarised in Table A1. In interpreting values of the photon index one should bear in mind that in the rexlillp model, the direct emission is modelled as a power law with exponential cut-off. Typical values of the cut-off energy $E_{\text{cut}}$ for this sources are in the 15-30 keV range. Therefore the actual slope of the spectrum is not well represented by solely the value of the slope $\Gamma$, but, rather, by combination of Gamma and $E_{\text{cut}}$. Variations of the slope with pulse phase are accompanied by corresponding variations of the $E_{\text{cut}}$ so that drastic variations of $\Gamma$ and $E_{\text{cut}}$ from one pulse phase bin to the other do not mean equally drastic variations of the shape of the continuum.

The presence of variations in the strength of the reflected component with the pulsar phase is further illustrated in Fig. 6 where the ratio of the spectra in different phase bins to a cutoffpl model with the same parameters is shown for several phase bins. One can see that the amplitude of the reflection features is indeed larger in the spectra for which the fit gave larger values of $f_{\text{eff}}$.

We find no evidence of the presence of the cyclotron scattering absorption feature (CSR) in phase-averaged and phase-resolved spectra in the 4–79 keV energy range.

We tried both lamp-post (rexlilllp) and corona (rexlill) models with no noticeable effect on the parameter values. The lamp-post geometry was motivated by the compactness of the accretion column compared to the inner disk radius that we envisaged. We also varied the lamp-post height, tried fixing it to 3, 5, 10 and 40 $R_g$ and found that it did not have any effect on the best-fit values of the parameters except for the normalisation of the the rexlillp model. Notably, $f_{\text{eff}}$ and cutoff energy/photon index did not change. It should be mentioned that both lamp-post and corona models are a significant simplifications of the true geometry of the system. However the agreement between the results we obtained under these geometries suggest that the exact geometry is not the critical parameter.

### 4 DISCUSSION

The presence of pulsations, i.e. lack of the propeller regime (Illarionov & Sunyaev 1975) down to the luminosity level of $\sim 3 \times 10^{34}$ erg s$^{-1}$ found by Doroshenko et al. (2020) implies that the dipole component of the magnetic field is not very strong. Based on this and a few other arguments Doroshenko et al. (2020) estimated the dipole field value of the pulsar $B \sim (3 - 9) \times 10^{12}$ G and coupling
Figure 5. The evolution of spectral parameters as the function of pulsar rotation phase for observations II, III, and IV. In each panel from top to bottom subplot: Pulse profile of the count rate in the 4–79 keV energy range; the reflection fraction parameter \( f_{\text{refl}} \), direct (red, dashed) and reflected (blue, solid) flux (4–50 keV) of the best-fitting model divided by the respective mean flux. All spectral parameters may be found in Fig. A1.

constant \( \xi \sim 0.1 – 0.2 \). For such field strengths and super-Eddington luminosity of \( L_X \sim 10^{39} \) erg s\(^{-1} \) at the peak of the light curve one may expect that the pulsar magnetosphere is fairly compact, with \( R_m \sim 150 – 500 \) km, i.e. \( R_m \sim 35 – 120R_p \) for a 1.4 \( M_\odot \) neutron star (Mushtukov et al. 2017; Tsygankov et al. 2018).

Given a rather small truncation radius, the disc will extend sufficiently close to the compact object, so that a radiation pressure dominated geometrically thick disc can form near the pulsar magnetosphere in the super-Eddington regime. Using formulæ from Shakura & Sunyaev (1973); Mushtukov et al. (2017) one may estimate the \( H/R \) at the inner edge of the disc
\[
\left( \frac{H}{R} \right)_m = 0.1 \frac{\xi^2}{\Omega^2} \left( \frac{R_m}{\Omega M_\odot} \right)^{-1} \left( \frac{R_m}{10^6 \text{cm}} \right)^{-1},
\]
with the parameters normalized to values appropriate for Swift J0243.6+6124. Substituting the values, one obtains \( H/R \sim 0.15 – 0.5 \) on the inner edge of the disc. Indeed, Doroshenko et al. (2020), based on the observed transitions in spectral and timing properties of the source, argued that between MJD 58045 and 58098 the inner part of the accretion disc was in the radiation pressure dominated regime. All three observations analysed in the present paper are within this time span.

Truncation of the geometrically thick accretion disc by the magnetic field of the neutron star will form a “well” with the pulsar located in its centre (see the sketch in Fig. 7). The inner edge of the “well” will be subject to continuous illumination by X-ray emission from the pulsar (Mushtukov et al. 2021), similar to illumination of the accretion disc in X-ray binaries and active galactic nuclei at more “normal” sub-Eddington accretion rates. However, unlike X-ray binaries at sub-Eddington accretion rate, the solid angle subtended by the inner edge of the thick accretion disc with \( H/R \approx 1 \) would be much larger. The solid angle of the inner edge of a disc with aspect ratio \( H/R = 1 \) is
\[
\Omega/4\pi = 2 \arctan(\xi R_m H/R) \sin \theta d\theta = 0.7 \times 4\pi \text{ sr}.
\]
Thus, \( \Omega/4\pi \approx 0.7 \text{ sr.} \) and the ballpark figure for equivalent width of the fluorescent line of iron is \( \sim \Omega/4\pi \times 1 \text{ keV} \sim 0.7 \text{ keV} \) assuming reflection from the optically thick material. This is compatible with the ob-
served equivalent width of the 6.4 keV line of the order of 1 keV (see sect. 3.2, also Tao et al. 2019). Similarly, the value of $f_{\text{eff}} \sim 0.25$ obtained in the spectral fits corresponds to $\Omega/4\pi \sim 0.29$, which is comparable with the value estimated above. We note however, that this crude estimate assumes an isotropic emission pattern, which is not strictly applicable to a magnetized neutron star.

Furthermore, we note that our best-fitting model predicts the inner radius of the accretion disc $\sim 50 - 70 R_\odot \sim (2 - 3) \times 10^7$ cm, with the typical uncertainty of $5 R_\odot$. This value is controlled by the line profiles in the iron line complex and was determined in the relxilllp model with the account for the Doppler and ionization effects (both of which contribute to the line broadening). This value of the inner disc radius estimated from the broadening of the line is consistent with the radius of the pulsar magnetosphere $\sim 3 \times 10^7$ cm estimated assuming the (dipole) magnetic field strength of $B = 3 \times 10^{12}$ G and the coupling parameter of $\xi = 0.2$ and (eq. 1 in Mushtukov et al. 2017). This consistency is quite remarkable because the two estimates are based on entirely different physical effects (Doppler-effect and disc-magnetosphere interaction) and are independent.

Thus, we hypothesise that the strong reflected emission originates at the inner edge of the thick accretion disc truncated by the magnetic field of the neutron star. The inner edge of the disc is irradiated by hard X-ray emission of an accretion column, as illustrated in Fig. 7. The pulsar emission diagram must be sufficiently broad so that the total reflected flux, as seen by the distant observer, does not vary much as the neutron star rotates. As the neutron star rotates, the pulsar beam sweeps through the line of sight giving rise to the direct emission pulsating with a much larger amplitude. These two components, weakly variable reflected emission and more strongly variable direct emission from the pulsar explain the overall behaviour of the pulse with strongly varying reflection fraction. In this picture, the anti-correlation of the reflection fraction and equivalent width of the fluorescent line of iron with the total flux is naturally explained. On the next level of detalization we may note that, as the pulsar emission is not isotropic, the irradiation pattern varies somewhat as the neutron star rotates, leading to some moderate variations of the reflected flux, which have however smaller fractional amplitude than the direct emission from the pulsar itself.

At the considered luminosity levels, the emission diagram of the pulsar is likely of the fan-like geometry, i.e. sufficiently broad, the pencil-beam being subdominant, if any. In this regime, the radiation escapes a super-critical accretion column mostly via its sides, leading to a fan-like emission pattern (Basko & Sunyaev 1976; Lyubarskii & Sunyaev 1982; Mushotukov et al. 2015; Mushotukov & Tsygankov 2022). Fan-beam naturally produces weakly variable irradiation of the inner disc edge, due to rather high degree of symmetry of the fan beam as seen from the accretion wall, and, importantly, two-peaked X-ray profiles are observed in this state. This is opposite to pencil-beam geometry (expected at smaller accretion rates) when photons escape primarily along the magnetic axis of the pulsar (Gnedin & Sunyaev 1973) and we expect a one-peaked pulse profile and little irradiation (Koliopanos & Gilfanov 2016). Variability of the direct emission is caused by the rotation of the fan- and pencil-beam emission components, the latter being sub-dominant at considered luminosities. The suggested picture explains observed behaviour with variable direct emission flux and variable reflection fraction, but significantly less variable reflected flux.

One can estimate the beaming factor of the pulsar comparing reflected and direct flux as follows. Using observation II as an example, the reflected flux in the average spectrum amounts to $\sim 2$ (in units of $10^{-8}$ erg s$^{-1}$ cm$^{-2}$), X-ray albedo varies depending on the ionization state and incidence angles, but generally, it is greater than $\sim 0.3$ (Basko et al. 1974; Zycki et al. 1994). Taking into account X-ray albedo we estimate the effective angle-averaged direct emission required to produce observed reflected emission as $\sim 2/0.3 = 6$ (in the same units). Observed direct flux is 12, which is about two times higher than the former figure. The ratio of the two flux values gives an estimate of the beaming factor of the order of $\sim 2$, i.e. beaming of the pulsar emission is rather weak, and the measured luminosity is fairly close to the real one. Beaming of radiation in X-ray pulsars is discussed, for example, in King & Lasota (2019); Mushtukov et al. (2021).

Outside the outburst peak, at the sub-Eddington accretion rates, the accretion disc returns to the normal geometrically thin state characterised by a rather low reflection fraction, typical for accreting X-ray pulsars, i.e. iron equivalent width $\sim 100$ eV (e.g. Bykov et al. 2021).

With the advent of X-ray polarimetry instruments (e.g. The Imaging X-ray Polarimetry Explorer, IXPE, Weisskopf et al. (2016)) it may be anticipated that studies of the variability of polarization and its energy dependence will bring new interesting results. Reflected (reprocessed) emission is expected to have a smaller degree of polarization than radiation coming from the accretion columns (Basko & Sunyaev 1975). The degree of polarization can be used to disentangle the direct pulsar emission from the reflected and/or thermal components, which brings the model-independent way to study the reprocessed emission and hence the matter distribution in such systems.

5 CONCLUSION

We analysed NuSTAR data of the ultra-luminous X-ray pulsar Swift J0243.6+6124 in the super-Eddington state. In this state, the spectrum of the source shows strong reflection signatures (fluorescent lines of iron with the equivalent width of $\sim 1$ keV, smeared K-edge and Compton hump) suggesting that the spectrum is dominated by the reflected emission. Pulse phase-resolved spectral analysis using...
a reflection model demonstrated significant modulation of the reflection fraction $f_{\text{refl}}$. However, a more careful look at the data revealed that this modulation is caused by variations of the direct emission, the reflected flux being significantly less variable.

We hypothesized that due to the large accretion rate and relatively moderate dipole magnetic field strength in this pulsar, the configuration is realized when the geometrically thick radiation pressure dominated accretion disc is truncated close to the neutron star, at the distance of $\sim 50 - 75 R_g$. The inner edge of the truncated accretion disc is filling a large solid angle as seen from the pulsar and is continuously illuminated by the X-ray radiation from the accretion column. The beaming factor of the emission is not large so that the radiation has a sufficiently broad fan-like emission diagram, expected at these large luminosities. This gives rise to the strong and weakly variable reflected emission. As the emission from the accretion column sweeps through the line of sight, we see direct emission of the accretion column, which is much more variable.

From the spectral analysis, based on the width of the iron lines and with the account for the photo-ionization of the material at the inner edge of the accretion disc we estimate its radius to be $\sim 50 - 70 R_g$. This value is remarkably consistent with the magnetospheric radius predicted given the constraints on the neutron star magnetic field strength and coupling parameter.

The uniqueness of this pulsar is explained by the combination of the moderately super-Eddington accretion rate with the moderate magnetic field strength.

ACKNOWLEDGEMENTS

We thank the anonymous referee for useful and constructive comments and suggestions which helped to improve the presentation of our results. Sergei Bykov acknowledges support from and participation in the International Max-Planck Research School (IMPRS) on Astrophysics at the Ludwig-Maximilians University of Munich (LMU). This work was partially supported by the grant 14.W03.31.0021 of the Ministry of Science and Higher Education of the Russian Federation.

Facility: NuSTAR (Harrison et al. 2013).

Software: NumPy (Harris et al. 2020), Matplotlib (Hunter 2007), SciPy (Virtanen et al. 2020), AstroPy (Astropy Collaboration et al. 2018), Pandas (pandas development team 2020), HEASoft 10. Code used to produce the results of the paper would be available shortly after the publication 11.

DATA AVAILABILITY STATEMENT

We are grateful for the NuSTAR data to the High Energy Astrophysics Science Archive Research Center (HEASARC) Online Service 12 provided by the NASA/Goddard Space Flight Center. To download data of NuSTAR used in this work, one should use observations ID from sect. 2. Swift data for light curves are available from the links in sect. 3.1.

REFERENCES

Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, Astronomical Society of the Pacific Conference Series Vol. 101, Astronomical Data Analysis Software and Systems V. p. 17

Astropy Collaboration et al., 2018, AJ, 156, 123

Bailer-Jones C. A. L., Rybicki J., Fouesneau M., Mantelet G., Andrae R., 2018, AJ, 156, 58

Basko M. M., Sunyaev R. A., 1975, A&A, 2, 311

Basko M. M., Sunyaev R. A., 1976, MNRAS, 175, 395

Basko M. M., Sunyaev R. A., Titarchuk L. G., 1974, A&A, 31, 249

Bykov S. D., Filippova E. V., Gilfanov M. R., Tsygankov S. S., Lutovinov A. A., Molkov S. V., 2021, MNRAS, 506, 2156

Cenko S. B., et al., 2017, GRB Coordinates Network, 21960, 1

Dauser T., García J., Walton D. J., Eikmann W., Kallman T., McClintock J., Wilms J., 2016, A&A, 590, A76

Doroshenko V., et al., 2020, MNRAS, 491, 1857

Evans P. A., et al., 2007, A&A, 469, 379

García J., et al., 2014, ApJ, 782, 76

Gnedin Y. N., Sunyaev R. A., 1973, A&A, 25, 233

HI4PI Collaboration et al., 2016, A&A, 594, A116

Harris C. R., et al., 2020, Nature, 585, 357

Harrison F. A., et al., 2013, ApJ, 770, 103

Hunter J. D., 2007, Computing in Science & Engineering, 9, 90

Illarionov A. F., Sunyaev R. A., 1975, A&A, 39, 185

Jaisawal G. K., Naik S., Chenevez J., 2018, MNRAS, 474, 4432

Jaisawal G. K., et al., 2019, ApJ, 885, 18

Jire J., et al., 2022, arXiv e-prints, p. arXiv:2203.12227

Kennea J. A., Lien A. Y., Krimm H. A., Cenko S. B., Siegel M. H., 2017, The Astronomer’s Telegram, 10809, 1

King A., Josota J., 2021, MNRAS, 485, 3588

Koliopanos F., Gilfanov M., 2016, MNRAS, 456, 3535

Kong L. D., et al., 2020, ApJ, 902, 18

Kong L.-D., et al., 2022, ApJ, 933, L3

Kouroubatzakis K., Reig P., Andrews J., A. Z., 2017, The Astronomer’s Telegram, 10822, 1

Lyubarskii Y. E., Sunyaev R. A., 1982, Soviet Astronomy Letters, 8, 330

Mushotkov A., Tsygankov S., 2022, arXiv e-prints, p. arXiv:2204.14185

Mushotkov A. A., Suleimanov V. F., Tsygankov S. S., Poutanen J., 2015, MNRAS, 447, 1847

Mushotkov A. A., Suleimanov V. F., Tsygankov S. S., Ingram A., 2017, MNRAS, 467, 1202

Mushotkov A. A., Portegies Zwart S., Tsygankov S. S., Nagirner D. I., Poutanen J., 2021, MNRAS, 501, 2424

Reig P., Fabregat J., Alfonso-Garzon J., 2020, A&A, 640, A35

Ross R. F., Fabian A. C., 2005, MNRAS, 358, 211

Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337

Tao L., Feng H., Zhang S., Bu Q., Zhang S., Qu J., Zhang Y., 2019, ApJ, 873, 19

Tsygankov S. S., Doroshenko V., Lutovinov A. A., Mushotkov A. A., Poutanen J., 2017, A&A, 605, A39

Tsygankov S. S., Doroshenko V., Mushotkov A. A., Lutovinov A. A., Poutanen J., 2018, MNRAS, 479, L134

Virtanen P., et al., 2020, Nature Methods, 17, 261

Wang P. J., et al., 2020, MNRAS, 497, 5498

Weisskopf M. C., et al., 2016, in den Herder J.-W. A., Takahashi T., Bautz M., eds, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, p. 990517, doi:10.1117/12.2235240

Wilson-Hodge C. A., et al., 2018, ApJ, 863, 9

Zhang Y., et al., 2019, ApJ, 879, 61

Zycki P. T., Krolik J. H., Zdziarski A. A., Kallman T. R., 1994, ApJ, 437, 597

pandas development team T., 2020, pandas-dev/pandas: Pandas, doi:10.5281/zenodo.3509134, https://doi.org/10.5281/zenodo.3509134
APPENDIX A: PHASE-RESOLVED PARAMETERS

This paper has been typeset from a \TeX/LaTeX file prepared by the author.
Figure A1. The evolution of spectral parameters as the function of pulsar rotation phase for observations II, III and IV. In each panel from top to bottom subplot: Pulse profile of the count rate in the 4–79 keV energy range; the reflection fraction parameter $f_{\text{refl}}$; direct (red, dashed) and reflected (blue, solid) flux (4–50 keV) of best-fitting model divided by the respective mean flux; e-folding energy of the continuum $E_{\text{cut}}$; Photon index $\Gamma$; normalization of relxilllp model. Two phase intervals are plotted.
Figure A2. As in Fig. 4 but for spectra of different rotational phases in observation II, III and IV (color of the a spectrum corresponds to the color of a phase-bin in the pulse profile inset). In the legend the reflected fraction $f_{\text{refl}}$ of the relxilllp model is shown for a given bin.
| phase     | $f_{\text{eff}}$ | $F_{\text{eff}}$ ($10^{-8}$ erg cm$^{-2}$ s$^{-1}$) | $F_{\text{dir}}$ ($10^{-8}$ erg cm$^{-2}$ s$^{-1}$) | $E_{\text{cut}}$, keV | $\Gamma$ | norm         |
|-----------|-----------------|---------------------------------|-----------------|-----------------|--------|-------------|
| II (90302319004) |                |                                 |                 |                 |        |             |
| 0.05      | 0.14 ± 0.01     | 1.46                             | 13.0            | 22.3$^{+0.7}_{-0.6}$ | 1.38 ± 0.02 | 0.62 ± 0.01 |
| 0.15      | 0.131 ± 0.010   | 1.57                             | 15.0            | 21.6 ± 0.6     | 1.38 ± 0.02 | 0.72 ± 0.01 |
| 0.25      | 0.23 ± 0.02     | 1.57                             | 9.2             | 15.5 ± 0.5     | 1.16 ± 0.03 | 0.38 ± 0.01 |
| 0.35      | 0.34 ± 0.02     | 1.50                             | 6.3             | 13.7 ± 0.5     | 0.95 ± 0.04 | 0.225 ± 0.007 |
| 0.45      | 0.17 ± 0.01     | 1.52                             | 11.1            | 21.1 ± 0.6     | 1.34 ± 0.02 | 0.51 ± 0.01 |
| 0.55      | 0.120 ± 0.009   | 1.67                             | 17.7            | 27.8 ± 0.9     | 1.46 ± 0.02 | 0.90 ± 0.02 |
| 0.65      | 0.121 ± 0.009   | 1.74                             | 18.3            | 29.7 ± 1.0     | 1.43 ± 0.02 | 0.90 ± 0.02 |
| 0.75      | 0.18 ± 0.01     | 1.67                             | 11.3            | 23.3$^{+0.7}_{-0.6}$ | 1.22 ± 0.02 | 0.474 ± 0.010 |
| 0.85      | 0.37 ± 0.02     | 1.16                             | 5.5             | 11.6 ± 0.4     | 0.54 ± 0.05 | 0.157$^{+0.005}_{-0.004}$ |
| 0.95      | 0.29 ± 0.02     | 1.31                             | 6.2             | 14.6$^{+0.6}_{-0.5}$ | 0.98 ± 0.04 | 0.225 ± 0.007 |
| III (90302319006) |                |                                 |                 |                 |        |             |
| 0.05      | 0.17 ± 0.01     | 4.92                             | 30.9            | 22.2 ± 0.7     | 1.37 ± 0.02 | 1.47 ± 0.04 |
| 0.15      | 0.16 ± 0.01     | 4.88                             | 32.8            | 25.5 ± 0.8     | 1.39 ± 0.02 | 1.57 ± 0.04 |
| 0.25      | 0.17 ± 0.01     | 4.06                             | 25.3            | 30 ± 1         | 1.39 ± 0.02 | 1.21 ± 0.03 |
| 0.35      | 0.33 ± 0.03     | 2.85                             | 9.5             | 17.2 ± 0.8     | 1.14 ± 0.04 | 0.38 ± 0.02 |
| 0.45      | 0.48 ± 0.03     | 2.13                             | 6.7             | 11.0 ± 0.5     | 0.58 ± 0.08 | 0.198 ± 0.008 |
| 0.55      | 0.34 ± 0.03     | 2.90                             | 10.0            | 15.2$^{+0.7}_{-0.6}$ | 1.16 ± 0.04 | 0.41 ± 0.02 |
| 0.65      | 0.21 ± 0.02     | 3.28                             | 16.5            | 19.5$^{+0.6}_{-0.5}$ | 1.39 ± 0.02 | 0.81 ± 0.02 |
| 0.75      | 0.31 ± 0.03     | 2.98                             | 11.2            | 15.7$^{+0.6}_{-0.5}$ | 1.27 ± 0.04 | 0.51 ± 0.02 |
| 0.85      | 0.43 ± 0.03     | 3.23                             | 9.0             | 14.2 ± 0.6     | 1.12$^{+0.04}_{-0.05}$ | 0.36 ± 0.02 |
| 0.95      | 0.21 ± 0.02     | 3.79                             | 19.2            | 20.7 ± 0.6     | 1.37 ± 0.02 | 0.92 ± 0.03 |
| IV (90302319008) |                |                                 |                 |                 |        |             |
| 0.05      | 0.157 ± 0.009   | 0.33                             | 3.7             | 13.8 ± 0.3     | 0.54 ± 0.03 | 0.106 ± 0.002 |
| 0.15      | 0.109 ± 0.008   | 0.35                             | 4.8             | 16.6$^{+0.4}_{-0.3}$ | 0.77 ± 0.02 | 0.155 ± 0.002 |
| 0.25      | 0.087 ± 0.007   | 0.40                             | 6.1             | 18.4 ± 0.4     | 0.92 ± 0.02 | 0.210 ± 0.003 |
| 0.35      | 0.075 ± 0.007   | 0.34                             | 6.5             | 16.7 ± 0.3     | 0.83 ± 0.02 | 0.213 ± 0.003 |
| 0.45      | 0.104$^{+0.008}_{-0.007}$ | 0.32                             | 5.1             | 16.1 ± 0.3     | 0.67 ± 0.02 | 0.157 ± 0.002 |
| 0.55      | 0.091$^{+0.007}_{-0.006}$ | 0.41                             | 6.2             | 19.7 ± 0.4     | 0.82$^{+0.01}_{-0.02}$ | 0.206 ± 0.003 |
| 0.65      | 0.074 ± 0.006   | 0.37                             | 7.2             | 19.5 ± 0.4     | 0.86$^{+0.01}_{-0.02}$ | 0.244$^{+0.003}_{-0.004}$ |
| 0.75      | 0.068 ± 0.006   | 0.40                             | 7.7             | 20.1 ± 0.4     | 0.88 ± 0.01 | 0.262 ± 0.003 |
| 0.85      | 0.071 ± 0.006   | 0.35                             | 7.5             | 17.6 ± 0.3     | 0.72 ± 0.02 | 0.236 ± 0.003 |
| 0.95      | 0.119 ± 0.008   | 0.34                             | 4.8             | 14.8 ± 0.3     | 0.53 ± 0.02 | 0.139 ± 0.002 |

Table A1. Spectral parameters of all ten phase-bins of Swift J0243.6+6124 in phase-resolved analysis in three observations. The modelling details are described in sect. 3.3. The position of zero-phase is arbitrary.