SMC X-3: the closest ultraluminous X-ray source powered by a neutron star with non-dipole magnetic field

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{Received: accepted}

\textbf{ABSTRACT}

\textbf{Aims.} Magnetic field of accreting neutron stars determines their overall behaviour including the maximum possible luminosity. Some models require an above-average magnetic field strength ($\gtrsim 10^{13}$ G) in order to explain super-Eddington accretion rate in the recently discovered class of pulsating ultraluminous X-ray sources (ULXs). The peak luminosity of SMC X-3 during its major outburst in 2016–2017 reached $\sim 2.5 \times 10^{39}$ erg s$^{-1}$ comparable to that in ULXs thus making this source the nearest ULX-pulsar. Determination of the magnetic field of SMC X-3 is the main goal of this paper.

\textbf{Methods.} SMC X-3 belongs to the class of transient X-ray pulsars with Be optical companions, and exhibited a giant outburst in July 2016 – February 2017. The source has been observed during the entire outburst with the \textit{Swift}/XRT and \textit{Fermi}/GBM telescopes, as well as the \textit{NuSTAR} observatory. Collected data allowed us to estimate the magnetic field strength of the neutron star in SMC X-3 using several independent methods.

\textbf{Results.} Spin evolution of the source during and between the outbursts and the luminosity of the transition to so-called propeller regime in the range of $(0.3 - 7) \times 10^{39}$ erg s$^{-1}$ imply relatively weak dipole field of $(1 - 5) \times 10^{13}$ G. On the other hand, there is also evidence for much stronger field in the immediate vicinity of the neutron star surface. In particular, transition from super- to sub-critical accretion regime associated with cease of the accretion column, absence of cyclotron absorption features in the broadband X-ray spectrum of the source obtained with \textit{NuSTAR} and very high peak luminosity favor an order of magnitude stronger field. This discrepancy makes SMC X-3 a good candidate to posses significant non-dipolar components of the field, and an intermediate source between classical X-ray pulsars and accreting magnetars which may constitute an appreciable fraction of ULX population.

\textbf{Key words.} accretion, accretion disks – magnetic fields – stars: individual: SMC X–3 – X-rays: binaries

1. Introduction

Magnetic field of a neutron star (NS) defines observational properties for a broad range of systems. Strongly magnetized accreting NSs, or X-ray pulsars (XRPs), are among the most prominent NS systems and are being actively studied, particularly in connection with the possibility of super-Eddington accretion. The main source of information about the strength of magnetic fields in XRPs is associated with the so-called cyclotron scattering resonance absorption features (CSRF) observed in the energy spectra of some sources. Unfortunately, this method is restricted by a sensitivity and energy range of X-ray telescopes and relatively soft spectra of XRPs. This implies a very limited number of XRPs with known magnetic fields, all of which fall into a narrow range $B \sim (1 - 8) \times 10^{12}$ G (see review by [Walter et al. 2015]) defined by aforementioned selection effects. At the same time magnetic fields of very bright XRPs (including the pulsating ultraluminous X-ray sources, ULXs) are expected to be $\gtrsim 10^{13}$ G (Mushotkov et al. 2015), and it would be very important to find sources with similar fields among the ordinary accreting XRPs.

Fortunately, besides the spectroscopy, pulsars timing properties can be used to independently estimate the magnetic field strength. Accretion torque affecting the NS depend on the magnetosphere size and, although model-dependent (see, e.g., [Parfrey et al. 2016]), can be used to estimate the field.

Detection of a centrifugal inhibition of accretion, known as the propeller effect (Illarionov & Sunyaev 1975; Stella et al. 1986) can also be used to estimate the magnetosphere size and thus the magnetic field. The reliability of this approach has been recently demonstrated by [Tsygankov et al. 2016a] and [Lutovinov et al. 2017], who showed that the magnetic field values estimated from the propeller effect are in good agreement with measurements from independent methods (including the direct estimate based on the observed CSRF energies).

SMC X-3 was discovered with the SAS-3 observatory as a bright source in the Small Magellanic Cloud by [Clark et al. 1978]. The source was reported to have a luminosity of $7 \times 10^{37}$ erg s$^{-1}$ in the $2 - 11$ keV energy band, and a relatively hard spectrum (with photon spectral index of $\sim 1$). Despite of the early proposed optical identification (van Paradijs et al. 1977; Crampton et al. 1978) the nature of the source remained uncertain for a long time. Only in 2004, [Edge et al. 2004] using the \textit{Chandra} data had shown that the 7.78 s pulsar found by [Corbet et al. 2004] in the \textit{RXTE} data can be identified with...
2. Observations

2.1. Swift/XRT data

The best facilities for long-term monitoring programs in a broad range of fluxes are currently provided by the Swift observatory (Gehrels et al. 2004). During the current outburst regular observations of SMC X-3 were performed with the XRT telescope (Burrows et al. 2005) in the soft X-ray band (0.5–10 keV) providing both high sensitivity and flexibility. The data analyzed in this work were collected between MJD 57611 and MJD 57785.

The XRT telescope observed SMC X-3 in both Windowed Timing (WT; providing good temporal resolution) and Photon Counting (PC) modes. Final scientific products (spectrum in each observation) were produced using online tools provided by the UK Swift Science Data Centre (Evans et al. 2009).

The spectra were grouped to have at least 1 count per bin and fitted using a simple power-law model modified with the photoelectric absorption (phabs/powerlaw model in the xspec package) and Cash statistic (Cash 1979). To avoid any problems caused by the calibration uncertainties at low energies we restricted the spectral analysis to the 0.7–10 keV and 0.5–10 keV energy bands for the data in WT and PC modes, respectively.

We found that at all luminosities the spectra of SMC X-3 can be well described with a simple absorbed power-law model with the photon index of $\Gamma = 0.5$ and the folding energy of $E_{\text{fold}} \approx 12$ keV. Additionally a black body component with the temperature of $kT \approx 1.78$ keV and an emission line from neutral iron with equivalent width of 70 eV were observed in the spectrum (Pottschmidt et al. 2016). It is important to emphasize that no other obvious spectral features, including the CSRF, were reported (Pottschmidt et al. 2016).

Extremely high bolometric luminosity of the source $L_{\text{peak}} \approx 2.5 \times 10^{39}$ erg s$^{-1}$, reached during this outburst, makes SMC X-3 a unique among transient X-ray pulsars with Be optical companions (Be/XRFs). In fact, due to the high luminosity it can be formally attributed to the group of ULXs. Its proximity to us would make it the closest ULX in this case, and furthermore, the closest ULX-pulsar. In this work we present results of the monitoring program conducted with the Swift/XRT and Fermi/GBM telescopes, as well as the NuSTAR observatory during recent outburst in July 2016 – February 2017. These data allowed us to estimate the magnetic field strength of the NS in the system using several independent methods and to conclude that the source likely has a non-dipole configuration of the magnetic field.

2.2. NuSTAR data

The NuSTAR observatory consists of two co-aligned identical X-ray telescope systems (FPMA and FPMB) operating in a wide energy range from 3 to 79 keV (Harrison et al. 2013). Thanks to the unique multilayered mirrors, NuSTAR has an unprecedented sensitivity in hard X-rays (> 10 keV) and is ideally suited for the broadband spectroscopy of different objects, including X-ray pulsars, and searching for the CSRFs in their spectra.

SMC X-3 has been observed with NuSTAR twice during the current outburst (ObsIDs 90201035002 and 90201041002) with the aim of measuring its hard X-ray spectrum. Preliminary results of the analysis of the first observation were discussed above (Pottschmidt et al. 2016). The second observation was performed at our request three months later on MJD 57704.

1 http://www.swift.ac.uk/user_objects/
2 http://www.swift.ac.uk/analysis/xrt/digest_cal.php

Fig. 1. The bolometric correction factor as a function of the source intensity (open circles). Filled circles show the dependence of the ratio of the total flux in 0.5 – 10 keV plus 15 – 50 keV to the 0.5 – 10 keV flux as a tracer of the bolometric correction factor ($K_{\text{bol}}$). Red crosses show the $K_{\text{bol}}$ value and the source flux (in 0.5 – 10 keV range) from the broadband spectra collected with the NuSTAR observatory.
when the source luminosity was \(\sim 1.9 \times 10^{38} \text{ erg s}^{-1}\) that is an order of magnitude lower in comparison to the first observation.

The raw observational data were processed to produce cleaned event files for the FPMA and FPMB modules using the standard \textit{NuSTAR} Data Analysis Software (\textsc{NuSTARDAS}) v1.6.0 provided under HEASOFT v6.19 with the CALDB version 20160502. Using the \textsc{nuproducts} routine, we extracted the source spectra from the circular region with radius of 120\(^\circ\). The background spectrum was extracted in the region of the same radius located 5\(^\circ\) from the source position.

### 2.3. Bolometric correction

For any meaningful discussion of the observed source properties a bolometric correction has to be estimated for the observed flux in soft energy band. To do that we used two available \textit{NuSTAR} observations as reference points and the dependence of the ratio of the total source flux in the 0.5 – 10 keV plus 15 – 50 keV energy bands to the source flux in the 0.5 – 10 keV energy band. The flux in the 15 – 50 keV band has been estimated using \textit{Swift}/BAT transient monitor\(^3\) light curve of the source. The ratio \(\langle F_{0.5-10\text{keV}} + F_{15-50\text{keV}} \rangle/F_{0.5-10\text{keV}}\) as a function of \(F_{0.5-10\text{keV}}\) is shown in Fig. 1 with filled circles. To convert this ratio to the bolometric correction factor \(K_{\text{bol}}\), we rescaled it to match the values calculated from the spectral parameters obtained from two \textit{NuSTAR} observations (marked by red crosses). The result of this adjustment shown with the open circles was fitted with a broken linear model (shown with the grey dashed line in the same figure). We estimate that residual systematic uncertainty in the correction factor does not exceed 5\%. Due to unknown shape of the source broadband spectrum at low fluxes we fixed the bolometric correction factor at 2 for all observations with \(F_{0.5-10\text{keV}} < 4 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}\). In the following analysis we apply this correction to all observational data and refer to the bolometrically corrected fluxes and luminosities, unless stated otherwise.

### 3. Results

The light curve of SMC X-3 observed with the \textit{Swift}/XRT telescope is shown in the upper panel of Fig. 2 with black points. The source flux was estimated using the bolometric and absorption corrections described above and assuming a distance to the source of 62 kpc \cite{Haschke2012}. The observed light curve looks rather complicated. One can see from Fig. 2a clear transition to a faster luminosity decay after MJD ~57710. This transition can be understood in terms of the thermal-viscous instability model as a moment when temperature at the outer radius of the accretion disk reached the critical temperature of \(\sim 6500 \text{ K}\) causing the decrease of the local viscosity and corresponding a decline of the mass accretion rate onto the compact object (see, e.g., \textsc{Lasota} 2001). This results in the fast decay of the luminosity observed, particularly, from XRPs in the very end of their outbursts (see recent works by \textsc{Tsygankov et al.} 2016a; \textsc{Lutovinov et al.} 2017).

As can be seen from Fig. 2 this decay is not smooth and was interrupted with temporal re-brightenings twice on MJD ~57730 and MJD ~57770. Such behaviour of the source in the end of the outburst is likely a result of additional inflow of matter to the accretion disk during the periastron passages (shown with the green vertical dotted lines assuming the orbital ephemeres

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\(^3\) http://swift.gsfc.nasa.gov/results/transients/
the broadband spectrum of SMC X-3 (upper panel) measured with Swift/XRT telescope (green points) and two NuSTAR modules FPMA and FPMB (red and blue points, respectively). Black solid line represents the best fit model consisting of exponentially cutoff power-law with addition of the fluorescent iron line. Corresponding residuals to the best-fit model are shown in the lower panel.

Fig. 3. The broadband spectrum of SMC X-3 (upper panel) measured with Swift/XRT telescope (green points) and two NuSTAR modules FPMA and FPMB (red and blue points, respectively). Black solid line represents the best fit model consisting of exponentially cutoff power-law with addition of the fluorescent iron line. Corresponding residuals to the best-fit model are shown in the lower panel.

trum model was modified by addition of the gabs component from the xspec package. The CSRF energy $E_{\text{cyc}}$ was varied within the 6–62 keV energy range with the step of 3 keV. A corresponding line width was varied within the 4–8 keV range with the step of 2 keV. Each combination of the lines position and width were fixed and the resulting model was used to approximate the source spectrum. As a result, none of such combinations resulted in a significant improvement of the fit and only the upper limit for the optical depth of $\sim 0.19$ ($3\sigma$) can be obtained.

Finally, we performed also a pulse phase-resolved spectroscopy of the emission of SMC X-3 using the NuSTAR data. It was found that the source spectrum at different phases is well described with the same model as was used for the average spectrum. The photon index and folding energy are slightly varying with the pulse phase in the ranges of $0.5 - 0.7$ and $E_{\text{fold}} \sim 11 - 15$ keV, respectively. Again, no indications for the CSRF were found in these spectra.

3.2. Orbital parameters

To determine the pulse frequency of the source we used the XRT window-timing mode event data which has sufficient counting statistics and time resolution. After applying the standard filtering criteria, we selected events with energies $0.3 - 10$ keV from the source-centered circle with radius of 25 pixels and applied barycentric correction to the photon arrival times. To determine the spin frequency of the source for each observation we performed a search for significant peaks around the source pulse period using the H-test (de Jager et al. 1989). To estimate the uncertainty of the obtained value we used the same approach as Markwardt et al. (2002), i.e. assumed that one sigma uncertainty for the most significant frequency peak in periodogram corresponds to the drop $\Delta F^2 \sim 1$ with respect to the peak value. The results are presented in Fig. 4 and are consistent with values reported by Fermi/GBM pulsar project (Townsend et al. 2017, Weng et al. 2017).

Note that modulation of the pulse frequency associated with the orbital motion is apparent and has to be taken into the account when determining the intrinsic spin frequency of the NS.

Note: Parameters are based on the full sample of the Fermi/GBM and Swift/XRT data. Uncertainties are quoted at 1$\sigma$ confidence level including the model systematics. The fit statistics for the same parameters without inclusion of the model systematics is $\chi^2 = 3992$ for 91 dof.

Table 1. Best-fit orbital parameters of SMC X-3.

<table>
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<tr>
<th>Parameter</th>
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<td>Orbital period (d)</td>
<td>45.07(5)</td>
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<td>$a_\star \sin i$ (light seconds)</td>
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The parameters of the binary orbit were estimated for the current outburst by Townsend et al. (2017) and Weng et al. (2017), however, both works only use a subset of the available data, and are not fully consistent with each other. The discrepancies, particularly in the obtained orbital period value, likely arise due to the difficulties in modeling of complex intrinsic spin evolution of the source.

To obtain an improved orbital solution we followed the approach similar to that by Townsend et al. (2017), i.e. estimated the intrinsic spin frequency of the pulsar based on the expected accretion-induced spin-up. We note that angular momentum transferred to the NS by the accretion disk is proportional to the accretion rate and thus is expected to dominate the spin evolution of the NS at high luminosities. The details of interaction of the disk with the magnetosphere are not thus very important and it is sufficient to consider only the accelerating torque (which, however, still depends on the magnetosphere size) with the spin-up rate defined as (Lipunov 1982)

$$\dot{\nu} = M \sqrt{GMR_d/2\pi I},$$

where the inner disk radius $R_d = kR_A$ is assumed to constitute some fraction of the Alfvénic radius, and $I$ is NS moment of inertia. Note that this is essentially the same model as used by Townsend et al. (2017). The main difference is that we use the bolometric light curve rather than flux in the soft band to estimate the accretion rate $M = R_NS L_X/GM$. Another difference is that we include also the spin frequency measurements reported by Fermi/GBM into the fit to improve statistics. Finally, Townsend et al. (2017) do not account for the model systematics associated with the fact that uncertainties in the observed accretion rate inevitably translate to a systematic uncertainty in the predicted frequency when integrating over the outburst. On the other hand, this uncertainty can be easily estimated directly from the dispersion of model predictions for a set of light curves simulated based on the observed fluxes and uncertainties (once initial estimate for $R_d$ is obtained). We estimated the model systematics to increase from zero at the beginning of the outburst to $\sim 2 \times 10^{-6}$ Hz at the end of the outburst, and added it in quadrature to the statistical uncertainties to obtain the final fit and estimate the uncertainties for the orbital parameters presented in Table 1. Note that using the bolometric light curve allows to obtain a much better fit than reported by Townsend et al. (2017) for model systematics.

Note: Parameters are based on the full sample of the Fermi/GBM and Swift/XRT data. Uncertainties are quoted at 1$\sigma$ confidence level including the model systematics. The fit statistics for the same parameters without inclusion of the model systematics is $\chi^2 = 3992$ for 91 dof.

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2016–2017 outburst is the magnetic field strength as well (Mushtukov et al. 2015a). The minosity (Basko & Sunyaev 1976; Mushtukov et al. 2015b). Critical due to the rise of the accretion column above the NS surface 2016). This reduces an impact of the radiative pressure and was as cross section is strongly reduced (see, e.g., Mushtukov et al. In the case of very strong magnetic field Compton scattering is observed (blue) pulse frequencies. Residuals for the best-fit model are also shown in the bottom panel.

4. Discussion

4.1. Critical and maximal luminosities

In the case of very strong magnetic field Compton scattering cross section is strongly reduced (see, e.g., Mushtukov et al. 2016). This reduces an impact of the radiative pressure and was shown to be required to allow the accreting X-ray pulsar to exhibit super-Eddington luminosities during giant outbursts similar to one observed from SMC X-3. Particularly, it is possible due to the rise of the accretion column above the NS surface (Basko & Sunyaev 1976; Mushtukov et al. 2015b). Critical luminosity \( L_c \) dividing two regimes of accretion is a function of the magnetic field strength in the vicinity of the NS surface. Therefore, observational constraint of \( L_c \) can be used to obtain independent estimates of the magnetic field. It is worth to note here that observational evidence of a transition through the critical luminosity was recently found in the classical XRP V 0332+53 (Doroshenko et al. 2017).

It is interesting that SMC X-3 exhibits a substantial change of its pulse profile between MJD \( \sim 57680 \) and MJD \( \sim 57700 \) when its main peak shifted by \( \sim \pi/2 \) (see Fig. 4 in Weng et al. 2017). We argue that this change happen when the bolometric luminosity of the source was \( \sim (2 - 3) \times 10^{38} \, \text{erg} \, \text{s}^{-1} \) is caused by the disappearance of the accretion column and corresponding modification of the intrinsic X-ray beaming from the pulsar (Gnedin & Sunyaev 1973). Interpretation of this luminosity as a critical one results in the estimates of the magnetic field of \( B = (2 - 3) \times 10^{13} \, \text{G} \) (Mushtukov et al. 2015b).

Maximal accretion luminosity of the NS depends on the magnetic field strength as well (Mushtukov et al. 2015d). The bolometric peak luminosity of SMC X-3 achieved during the 2016–2017 outburst is \( \sim 2.5 \times 10^{39} \, \text{erg} \, \text{s}^{-1} \) exceeding the Eddington limit by an order of magnitude. According to the accretion column theory by Mushtukov et al. (2015a) so high luminosity is impossible if the NS magnetic field is less than \( \sim 2 \times 10^{13} \, \text{G} \). This value agrees well with the one derived above from the critical luminosity. Both methods refer to the magnetic field strength in the region of the main energy release, i.e., in immediate vicinity of the NS surface.

4.2. Accretion torque

Evolution of the intrinsic spin frequency of accreting pulsars is driven by angular momentum transfer from the accretion disk, and possibly by braking mechanisms associated with interaction of the magnetosphere with the disk (Ghosh & Lamb 1978; Wang 1998; Lovelace et al. 1995; Parfrey et al. 2016). In case of SMC X-3, however, the accelerating torque is expected to dominate, and indeed, as already mentioned in Section 2b no evidence for braking has been observed. The observed spin evolution is thus fully consistent with pure spin-up by the disk which is trivial to calculate and allows to estimate the magnetic field. As follows from Eq. (1), the magnetosphere size or, equivalently, magnetic field strength of the NS is one of the model parameters that can be obtained during the fit of the orbital parameters if physical parameters of the NS and relation of the inner disk and Alfvénic radii are known or assumed. For standard NS with mass and radius of 1.4\( M_\odot \) and 10 km respectively, and coupling factor \( k = 0.5 \) the field strength is well constrained at \( B \sim 2.55(1) \times 10^{12} \, \text{G} \). This is consistent with the value reported by Klus et al. (2014) based on the spin evolution between outbursts, and an order of magnitude lower than estimated based on the observed critical and maximal luminosities.

4.3. Propeller effect

The distinctive property of accretion onto the highly magnetized NS is a strong centrifugal barrier produced by the rotating magnetosphere. This barrier does not allow the accreting matter to penetrate into the magnetosphere if the velocity of the field lines is higher than corresponding local Keplerian velocity, that is known as propeller effect (Illarionov & Sunyaev 1973; Stella et al. 1984). In other words the accretion is only possible if the magnetospheric radius \( R_m \) does not exceed the co-rotation radius \( R_c \).

Because the magnetospheric radius depends on the mass accretion rate, we can link the transition luminosity \( L_{\text{lim}} \) with the spin period of the NS and its magnetic field strength. The corresponding equation can be derived by the equating the magnetospheric radius to the co-rotation radius (e.g., Campana et al. 2002).

\[
L_{\text{lim}}(R) \approx \frac{GM_{\text{NS}}M}{R} \approx 4 \times 10^{37} k^{7/2} B_{12}^{2} P^{-7/3} M_{1.4}^{-2/3} R_{6}^{5} \, \text{erg s}^{-1},
\]

where \( P \) is the NS spin period in seconds, \( B_{12} \) is the strength of the dipole component of the magnetic field in units of \( 10^{12} \, \text{G} \), \( M_{1.4} \) and \( R_{6} \) are the NS mass and radius in units of 1.4\( M_\odot \) and 10\(^6 \) cm, respectively. A factor \( k \) relates the magnetospheric radius to the classical Alfvén radius in the case of disc accretion and is usually taken \( k = 0.5 \) (Ghosh & Lamb 1978).

On 2017 February 1, SMC X-3 was still very bright to expect the transition to the propeller regime for the NS with standard magnetic field. Therefore, we investigated the archival Swift/XRT and Chandra data. The archival Swift observations were analysed as described above. The source spectra available as part of the Chandra Source Catalog\(^5\) were fit using the xspec and the same model as for the Swift/XRT spectra. The resulting light curves based on all available data as well as 3\(\sigma \) upper limits are shown in Fig. 5.

From Fig. 5 one can see that SMC X-3 was significantly detected at low luminosities during several type I outbursts. The faintest state of the source with bolometric luminosity of

\(^5\) <http://cxc.harvard.edu/csc7/> [Evans et al. 2010]

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absorbed flux under assumption of the distance to the source $d$ (see Table 1) for illustrative purpose. The luminosity is calculated from the unabsorbed flux under assumption of the corresponding color. The historical data were shifted by an integer number of the orbital periods obtained in the current work (see Table 1) for illustrative purpose. The luminosity is calculated from the unabsorbed flux under assumption of the corresponding color. The historical data were shifted by an integer number of the orbital periods obtained in the current work.

A solid red vertical line indicates the dipole field estimate from the observed spin evolution of the source. Constraints on the field strength in vicinity of the NS based on the observed critical and maximal luminosities and CR SF non-detection are shown with vertical shaded region. Note an order of magnitude discrepancy between the field estimates at the magnetosphere and in vicinity of the NS.

A green vertical dotted line corresponds to the times of the periastron passages.

$3.5 \times 10^{34} \text{ erg s}^{-1}$ was observed by the Chandra observatory on 2006, April 26. Just one day before that the source was not detected with $3\sigma$ upper limit of $2.5 \times 10^{33} \text{ erg s}^{-1}$. The lowest significant luminosity of SMC X-3 can serve as an estimate for the threshold of the propeller regime onset ($L_{\text{lim}} \sim 3 \times 10^{34} \text{ erg s}^{-1}$). On the other hand, based only on the Swift/XRT data the limiting luminosity can be as high as $L_{\text{lim}} \sim 7 \times 10^{35} \text{ erg s}^{-1}$. Therefore, we use here very conservative range of luminosities from $3 \times 10^{34} \text{ erg s}^{-1}$ to $7 \times 10^{35} \text{ erg s}^{-1}$ to estimate the dipole component of the magnetic field (shown by horizontal dashed lines in Fig. 5). Substituting the measured spin period of SMC X-3 ($P = 7.81 \text{ s}$) and the range of limiting propeller luminosity $L_{\text{lim}}$ to the Eq. (4) and assuming the standard mass and radius of the NS we can estimate the dipole component of the NS magnetic field as $B \sim (1 - 5) \times 10^{12} \text{ G}$.

Interestingly, both methods (accretion torque and the propeller effect) measuring the dipole component of the magnetic field well agree with each other and give significantly lower strength in comparison to the methods sensitive to the magnetic field in the vicinity of the NS (critical and maximal luminosities, absence of the CS RF). This fact can point to the strongly non-dipole configuration of the NS magnetic field with multipoles by an order of magnitude stronger than dipole component within the emission region. Another possibility to resolve this discrepancy is significant deviation of the parameter $k$ from the standard value of 0.5 adopted in our study. Namely, the estimate of the dipole component of the magnetic field $B_{\text{dipole}}$ will coincide with multipole component $B_{\text{multipole}}$ for $k \approx 0.15$.

However, this assumption seems to be inconsistent with the results obtained previously for other sources. Indeed, up to date the propeller effect was observed in SAX J1808.4-3658 (Campana et al. 2003), GRO J1744-28 (Cui 1997), 4U 0115+63 (Tsygankov et al. 2016a), V 0332+63 (Tsygankov et al. 2016a), SMC X-2 (Lutovinov et al. 2017), and the accreting magnetar M82 X-2 (Tsygankov et al. 2016b). All these sources are compared with magnetic field strength measured independently (mainly based on the observed CR SF energy, see Tsygankov et al. 2016a, and references therein). Note that for all six sources the limiting luminosity seems to agree with the theoretical dependence given by Eq. (4) for $k = 0.5$ shown with dashed line.

### 5. Conclusion

In this paper we report the estimate of the magnetic field strength in a bright X-ray pulsar SMC X-3 which can be considered the closest ULX-pulsar. The source exhibited a giant outburst in July 2016 – February 2017 with the peak bolometric luminosity of $2.5 \times 10^{39} \text{ erg s}^{-1}$. The entire outburst had been monitored with the Swift/XRT and Fermi/GBM telescopes, as well as with the NuSTAR observatory. The collected data allowed us to estimate the magnetic field strength of the NS in SMC X-3 using several independent methods based on the spectral and timing properties of X-ray emission from the system.

The dipole component of the magnetic field was determined using the accretion torque models and observation of the transition to the propeller regime at the limiting luminosity in the range of $(0.3 - 7) \times 10^{39} \text{ erg s}^{-1}$ both resulting in relatively weak strength of about $(1 - 5) \times 10^{12} \text{ G}$. On the other hand, there is evidence for a much stronger field strength in the immediate vicinity of the NS surface. In particular the transition from super-
to sub-critical accretion regime associated with cease of an accretion column and very high peak luminosity favor the magnetic field of \(~(2-3) \times 10^{13}\) G. Absence of the CSRF in the broadband X-ray spectrum of the source obtained with NuSTAR is also consistent with this estimate.

This discrepancy makes SMC X-3 a good candidate for a NS with strong multipole configuration of the magnetic field, and an intermediate source between classical X-ray pulsars and accreting magnetars which may constitute an appreciable fraction of ULX population. Alternatively, this discrepancy can be resolved if one assumes that the accretion disc in SMC X-3 pushes much deeper into magnetosphere than normally expected. However, the reason for such behaviour would be unclear as it was not observed in other objects with wide range of luminosities for which similar solidification was conducted.

On the other hand, existence of higher field multipoles was also claimed for pulsating ULX-1 in NGC 5907 [Israel et al. 2016]. One can thus speculate that a complex structure of the NS magnetic field may thus be a common feature for this class of objects.

Acknowledgements. This work was supported by the Russian Science Foundation grant 14-12-01287 (SST, AAL, AAM), the Foundations’ Professor Pool, the Finnish Cultural Foundation and the Academy of Finland grant 268740 (JP). We also acknowledge the support from the COST Action MP1304.

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