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# SRG/ART-XC, *Swift*, NICER and *NuSTAR* study of different states of the transient X-ray pulsar MAXI J0903–531

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## ABSTRACT

The results of the broadband spectral and timing study of the recently discovered transient X-ray pulsar MAXI J0903–531 in a wide range of luminosities differing by a factor of  $\sim 30$  are reported. The observed X-ray spectrum in both states can be described as a classical pulsar-like spectrum consisting of the power-law with the high-energy cutoff. We argue that absence of the spectrum transformation to the two-hump structure expected at low fluxes points to a relatively weak magnetic field of the neutron star below  $(2\text{--}3) \times 10^{12}$  G. This estimate is consistent with other indirect constraints and non-detection of any absorption features which can be interpreted as a cyclotron absorption line. Timing analysis of the *NuSTAR* data revealed only slight variations of a single-peaked pulse profile of the source as a function of the energy band and mass accretion rate. In both intensity states the pulsed fraction increases from 40% to roughly 80% with the energy. Finally we were also able to obtain the orbital solution for the binary system using data from the *Fermi*/GBM, NICER and *NuSTAR* instruments.

**Key words.** accretion, accretion disks – magnetic fields – pulsars: individual: MAXI J0903–531 – stars: neutron – X-rays: binaries

## 1. Introduction

The transient X-ray source MAXI J0903–531 was discovered with the MAXI/GSC nova alert system on April 14, 2021 with an indication of the gradual increase of the flux (Yamaoka et al. 2021). An accurate source localisation with coordinates of  $\alpha_{J2000.0} = 136^{\circ}27866$ ,  $\delta_{J2000.0} = -53^{\circ}50518$  ( $2''8$  uncertainty radius at the 90% confidence level) was obtained two days later with the *Swift*/XRT telescope (Kennea et al. 2021). The same authors pointed to the possible optical counterpart, *Gaia* EDR3 source 5311384333263075840, with the distance estimated at around 10 kpc (Bailer-Jones et al. 2021). A subsequent discovery of coherent pulsations with the period of  $P = 14.055$  s (Ray et al. 2021) by the NICER telescope allowed then to unambiguously identify the object as a transient X-ray pulsar (XRP). A spectral type of the companion star B1.5–2 III-Ve was determined using observations at the Southern African Large Telescope (SALT; Monageng et al. 2021), suggesting that MAXI J0903–531 is a new Galactic Be X-ray binary system (Be/XRP).

Analysis of the long-term monitoring of the companion star from the ASAS-SN project revealed a strong modulation at a period of 3.84 days with an amplitude of 0.05 magnitudes (Monageng et al. 2021). Another periodicity at 0.79 days was found using the Transiting Exoplanet Survey Satellite (TESS) data, that could be interpreted as a pulsation period or a rotation period of a Be star (Rivera Sandoval et al. 2021). The presence of this periodicity was later confirmed using the OGLE survey data (Udalski 2021) although the authors suggested the 3.8 d periodicity

to be a 1-day alias of 0.79 d period. Later, based on the analysis of the long-term monitoring data from the *Swift*/BAT transient monitor and *Fermi*/GBM monitor another longer periodicity with period of around 57 days was found by Corbet et al. (2021). Assuming that this is the orbital period, the location of MAXI J0903–531 on the Corbet diagram (Corbet 1986) supports its Be/XRP classification.

Based on the NICER data it was shown that the 0.5–10 keV energy spectrum can not be described by just an absorbed power-law model, but an additional blackbody component with temperature of  $kT = 0.61 \pm 0.02$  keV is required (Ray et al. 2021). Closer to the end of the outburst, when MAXI J0903–531 faded to the 3–50 keV flux of  $1.35 \times 10^{-11}$  erg s<sup>-1</sup> cm<sup>-2</sup> (i.e., about 40 times lower in comparison to the peak of the outburst), the source was also observed with the *NuSTAR* observatory in the broad energy band (Thalhammer et al. 2021). It was shown that broadband energy spectrum can be fitted with an absorbed cut-off power-law model with photon index of 1.25 and folding energy of 27 keV. The absorption column density and blackbody component could not be constrained with the available data. MAXI J0903–531 demonstrates, therefore, clear transient behaviour and was observed in a very wide range of luminosities.

Both timing and spectral properties of accreting XRPs differ significantly at low and high mass accretion rates shedding light on different physical aspects of emission production and the interaction with matter in the presence of extreme magnetic fields. Here we focus, therefore, on reporting results of the detailed study of temporal and spectral properties of MAXI J0903–531

**Table 1.** Observations of MAXI J0903–531 used in the current work.

ObsID	$T_{\text{start}}$ MJD	$T_{\text{stop}}$ MJD	Exposure ks
<i>NuSTAR</i> observations			
90701315002	59337.12	59337.59	23.3
90701320002	59375.63	59376.76	48.0
SRG/ART-XC observations			
11001000100	59001.89	59002.72	0.05
12000600100	59188.75	59189.59	0.05
12110050001	59357.64	59357.71	5.9
13000600100	59370.93	59371.59	0.02
NICER observations			
4202120101	59320.82	59320.89	0.90
4202120102	59321.02	59321.99	6.58
4202120103	59322.24	59322.96	5.06
4202120104	59323.02	59323.61	4.58
4202120105	59324.51	59324.96	1.99
4202120106	59325.02	59325.16	1.47
4202120107	59326.45	59326.51	0.66
4202120108	59327.22	59327.55	0.88
4202120110	59329.42	59330.00	1.54
4202120111	59330.06	59330.97	1.92
4202120112	59331.09	59331.94	2.30
4202120113	59331.99	59332.13	1.23
4202120115	59335.93	59335.94	0.89
<i>Swift</i> observations			
00014281001 (wt)	59320.97	59321.11	1.98
00014281002 (wt)	59327.35	59327.69	1.00
00014281003 (wt)	59329.74	59330.62	2.32
00014281004 (wt)	59331.08	59331.29	0.65
00014281005 (wt)	59333.72	59333.80	0.68
00014281006 (pc)	59378.46	59378.47	0.89
00014281007 (pc)	59384.97	59384.98	0.95
00014281008 (pc)	59387.15	59387.23	0.87
00014281009 (pc)	59390.01	59390.02	0.92
00014281010 (pc)	59393.41	59394.00	1.53
00014281011 (pc)	59396.19	59396.20	0.97
00014281012 (pc)	59398.70	59398.91	1.52
00014281014 (pc)	59405.27	59405.28	0.95
00014281015 (pc)	59408.34	59408.35	0.28
00014281016 (pc)	59411.17	59411.18	0.87
00014281017 (pc)	59414.09	59414.10	0.77
00014281018 (pc)	59417.01	59417.02	0.86
00014281020 (pc)	59423.06	59423.07	0.80
00014281021 (pc)	59426.92	59426.92	0.24
00014281022 (pc)	59429.84	59429.85	0.89
00014281023 (pc)	59432.96	59432.97	0.84

using the data from various X-ray instruments in the broad energy band at mass accretion rates differ by a factor of  $\sim 30$ .

## 2. Data analysis

As already mentioned above, MAXI J0903–531 was observed with different X-ray and optical facilities since the discovery. Below we briefly describe the reduction procedures for each of the data-sets used in the current work. The list of the observations can be found in Table 1.

### 2.1. *NuSTAR*

The main instrument for our study is the *NuSTAR* observatory hosting two identical Focal Plane Modules A and B (FPMA and FPMB; Harrison et al. 2013) covering the broad energy range of 3–79 keV. *NuSTAR* observed MAXI J0903–531 twice: first time on May 3, 2021 (ObsID 90701315002), about two weeks after the discovery of the source and thus already closer to the end of an outburst at a comparatively low luminosity (Thalhammer et al. 2021). The second observation was performed on June 10, 2021 (ObsID 90701320002) following trigger by the SRG/ART-XC telescope which discovered the resumed activity of MAXI J0903–531, so the flux in the second observation is by a factor of 30 higher in comparison to the first *NuSTAR* pointing.

The data for both observations were reduced following the standard procedures described in the *NuSTAR* user guide, and using the standard *NuSTAR* Data Analysis Software *NuSTAR-DAS* v1.9.6 with the CALDB version 20210524. The source and background spectra and light curves were extracted from circular regions with radii of 50'' and 150'' in the low state (observation 90701315002), and 60'' and 150'' in the bright state (observation 90701320002), respectively. The background in both cases was extracted from a source-free region in the corner of the field of view. The scientific products were obtained using the *NUPRODUCTS* routine with the default parameters. Energy spectra were optimally rebinned using the prescription from Kaastra & Bleeker (2016). The lightcurves were background and baricentrically corrected. In order to increase statistics we added the lightcurves from both *NuSTAR* modules (FPMA and FPMB).

### 2.2. SRG/ART-XC

The *Spectrum Roentgen Gamma* (SRG) observatory (Sunyaev et al. 2021) hosts two X-ray telescopes: the Mikhail Pavlinsky ART-XC operating in the 4–30 keV energy range (Pavlinsky et al. 2021) and eROSITA operating in the 0.2–10 keV (Predehl et al. 2021). This mission aims at the most sensitive all-sky survey in the X-ray band.

SRG/ART-XC observed MAXI J0903–531 both during the surveys (on June 2, 2020, Dec 6, 2020, June 6, 2021) and during the technical stop (parking position) before the orbit correction on May 23, 2021. In the survey mode each source on the sky is observed once in half a year, with an exposure time on the order of several tens of seconds. In the low intensity state such an exposure allowed us to only detect the source and roughly estimate its flux. The exposure collected during the parking position is much longer (5.9 ks). This observation allowed us to measure the source spectrum and determine its flux very accurately. During the third all sky survey scan, on June 6, 2021, the source was also bright enough to reconstruct its spectrum with ART-XC. As was mentioned above this observation was a trigger for the follow-up observation with *NuSTAR*.

The ART-XC telescope consists of seven identical grazing incidence focusing modules with the total effective area of  $\sim 450$  cm<sup>2</sup> at 6 keV, energy resolution of 1.4 keV at 6 keV, angular resolution of  $\sim 50''$  and timing resolution of 23  $\mu$ s. ART-XC data were processed with the analysis software *ARTPRODUCTS* v0.9 and with ART-XC CalDB version 20200401. A description of the ART-XC telescope and the software can be found in Pavlinsky et al. (2021). All energy spectra were rebinned to have at least 1 count per energy channel.

### 2.3. NICER

Soon after discovery of the source, the *Neutron star Interior Composition Explorer* (NICER; Gendreau et al. 2012) started its monitoring with about one day cadence. The monitoring continued for almost 40 days and covered the whole outburst and some fraction of the quiescent period before the next outburst. In our work we use the NICER data collected until MAXI J0903–531 entered low-luminosity state when its flux became background dominated, i.e., above  $F_{0.5-10\text{keV}} \sim 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$  (or before MJD 59335).

The raw NICER data were reduced using the `NICERDAS` software version 7a with default filtering criteria applied. The background was estimated using the tool `NIBACKGEN3C50`<sup>1</sup> (Remillard et al., in prep.) with the default parameters. Each spectrum was binned to have at least 1 count per energy channel.

### 2.4. Swift

To study the long-term behaviour of the source including in the quiescent state, simultaneously with our *NuSTAR* observation in the bright state, we triggered a two-months monitoring of MAXI J0903–531 with the XRT telescope (Burrows et al. 2005) on-board the *Neil Gehrels Swift Observatory* (Gehrels et al. 2004) with cadence of 3 days. Depending on the source brightness the data were collected either in the photon counting (PC) or windowed timing (WT) mode. The spectra for each observation were extracted using the online tools (Evans et al. 2009) provided by the UK Swift Science Data Centre<sup>2</sup> and binned to have at least 1 count per energy channel.

## 3. Results

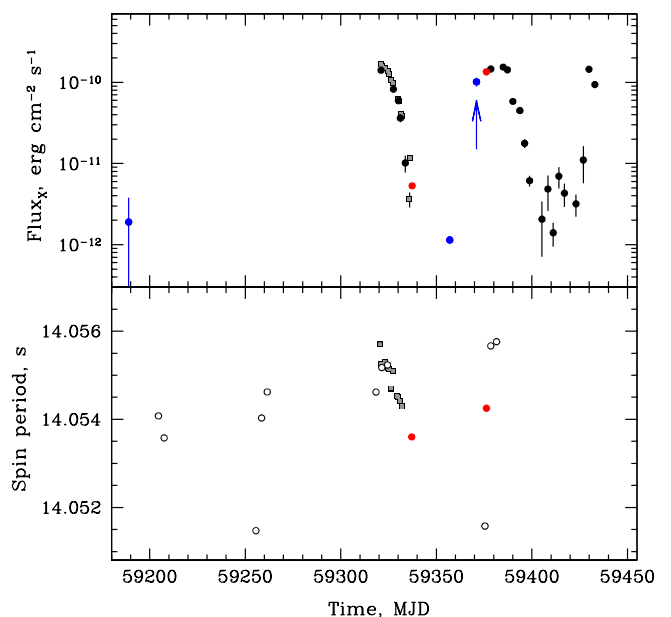
Using all available observations described above we are able to study temporal and spectral properties of MAXI J0903–531 at different time scales and mass accretion rates. The overall light curve of the source covering about four months of observations is presented in Fig. 1. In addition we discuss separately results obtained in two deep observations with *NuSTAR* which allow also detailed spectral analysis in broad energy band.

### 3.1. Timing analysis

MAXI J0903–531 demonstrates strong flux variability at different time scales. As was shown by Corbet et al. (2021), on the long time scale the source exhibits transient behaviour with period of around 57 days. The authors suggested that this activity is connected to periastron passages of the NS in an eccentric binary system. On short time scales flux from MAXI J0903–531 pulsates with the period of  $\sim 14$  s (Ray et al. 2021). Here we discuss variations of spin frequency and pulse profiles of the source throughout the outburst.

#### 3.1.1. Spin frequency changes and binary orbit

Using the background subtracted and baricentrically corrected light curves, we measured spin period of pulsar in all available NICER and *NuSTAR* observations applying standard epoch folding technique (`EFSEACH` tool from the `FTOOLS` package; Leahy 1987). Uncertainty on the spin period was estimated as described



**Fig. 1.** *Top:* The light curve of MAXI J0903–531 from the all available data. An observed flux is given in the 0.5–10 keV energy band for *Swift*/XRT (black) and NICER (gray), and in the 4–12 keV for SRG/ART-XC (blue) and *NuSTAR* (red). *Bottom:* Baricentrically corrected spin period of the pulsar obtained from *Fermi*/GBM (open circles), NICER (gray) and *NuSTAR* (red).

by Boldin et al. (2013). In addition, measurements provided by the *Fermi*/GBM XRP monitoring project<sup>3</sup> were also used. Low count statistics did not allow us to detect pulsations in the SRG/ART-XC data. Because no orbital parameters except for the tentatively identified 57-days orbital period are known, no binary correction was applied to the light curves for initial timing analysis. The resulting dependence of apparent spin period of MAXI J0903–531 on time is shown in the bottom panel of Fig. 1.

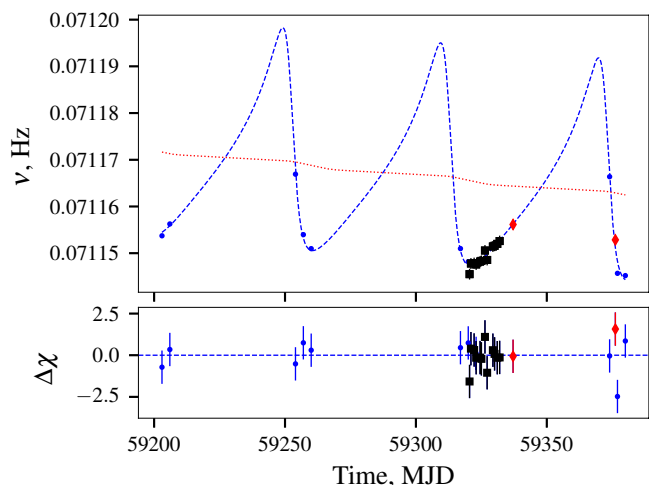
As can be seen from Fig. 1, both the observed spin frequency and flux of MAXI J0903–531 exhibit  $\sim 57$  d periodic variations likely associated with orbital modulation. Indeed, very strong apparent spin-down just before the outburst and gradual spin-up after the peak of the outburst is the opposite to what could be expected from an accreting neutron star under influence of accretion torque, and can only be explained by Doppler effect associated with orbital motion. On top of that a possible long-term spin-down trend is observed as was already mentioned by Corbet et al. (2021).

To recover intrinsic spin evolution of the pulsar and orbital ephemerides we conducted, therefore, modeling of the observed spin frequency changes. To model observed spin history we used approach similar to that used by Doroshenko et al. (2016). However, considering that only few measurements of spin frequency are available, and that those only cover limited orbital phase interval, we adopted a simplified approach. In particular, we described intrinsic spin history as a piecewise linear function characterized by steady spin-up/down during and between the outbursts, respectively. The frequency change rates were considered as free parameters in both cases but were assumed to equal for all burst/quiescence intervals. The reference epoch for spin-up episodes during the outbursts was assumed to coincide with pe-

<sup>1</sup> [https://heasarc.gsfc.nasa.gov/docs/nicer/tools/nicer\\_bkg\\_est\\_tools.html](https://heasarc.gsfc.nasa.gov/docs/nicer/tools/nicer_bkg_est_tools.html)

<sup>2</sup> [http://www.swift.ac.uk/user\\_objects/](http://www.swift.ac.uk/user_objects/)

<sup>3</sup> <https://gammaray.nsstc.nasa.gov/gbm/science/pulsars/lightcurves/maxij0903.html>



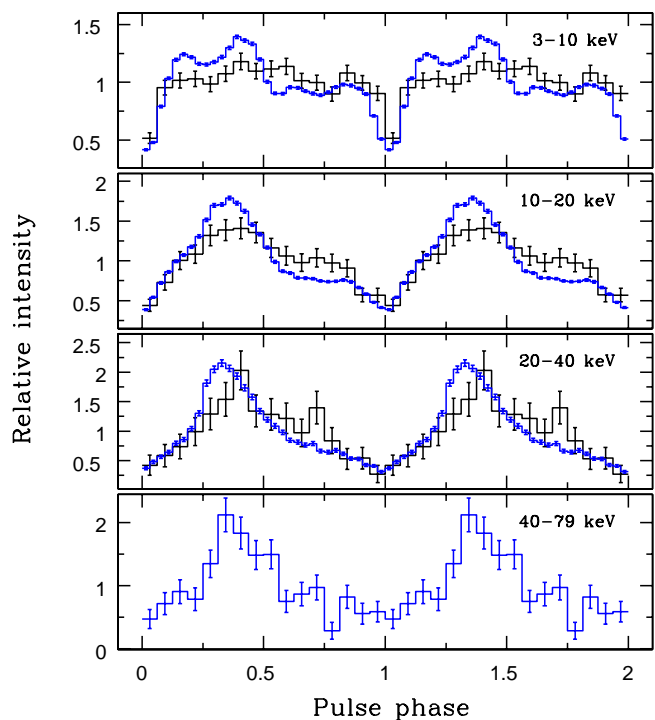
**Fig. 2.** Spin history of the source as observed by *Fermi*/GBM (blue dots), *NICER* (black squares) and *NuSTAR* (red diamonds). The final model including the intrinsic spin frequency variations (red) and those due to the orbital motion (blue) together with the best-fit residuals (lower panel) are also shown.

**Table 2.** Best-fit orbital parameters assuming constant spin-up during outbursts and spin-down between the outbursts. Uncertainties are reported at  $1\sigma$  confidence level.

Parameter	Value
$P_{\text{orb}}$ , d	60.3(1)
$a \sin i$ , lt. s	225(6)
$e$	0.56(4)
$\omega$ , deg	247(17)
$T_{\text{PA}}$ , MJD	59192(3)
$\nu_0$ , $10^{-2}$ Hz	7.1173(2)
$\dot{\nu}_o$ , $10^{-7}$ Hz d $^{-1}$	-2(5)
$\dot{\nu}_q$ , $10^{-8}$ Hz d $^{-1}$	-2(16)
$\chi^2/\text{dof}$	16.78/17

riastron passage, and quiescent periods were assumed to start fifteen days later (which corresponds to the approximate duration of the bright phase of the outburst where spin-up can be expected) as the reference epoch for inter-burst periods. To avoid jumps in the assumed spin frequency the resulting piece-wise function was in addition smoothed with fifteen days long Hann window. This actually mimics quite well the expected changes of spin frequency due to accretion torque in a series of short outbursts.

We emphasize that the model described above is just a rough approximation of actual intrinsic spin frequency changes. The available data, however, is insufficient to model it more accurately based on the observed flux like was done, i.e. in Tsygankov et al. (2017a); Doroshenko et al. (2018). On the other hand, also the accuracy of spin frequency measurements and contribution of intrinsic spin variations is lower for MAXI J0903–531, so accurate description of intrinsic frequency variations is less important. We verified, for instance, that the derived orbital parameters are almost unaffected if one assumes steady spin-down instead of the more complex model adopted above. This is also confirmed by the fact that best-fit spin-up rate for outbursts is both consistent with zero and expected spin-up rate for a neutron star with standard parameters accreting at observed luminosity of  $\sim 4.5 \times 10^{36}$  erg s $^{-1}$ . Indeed, an upper limit on the expected spin-up rate might be derived assum-

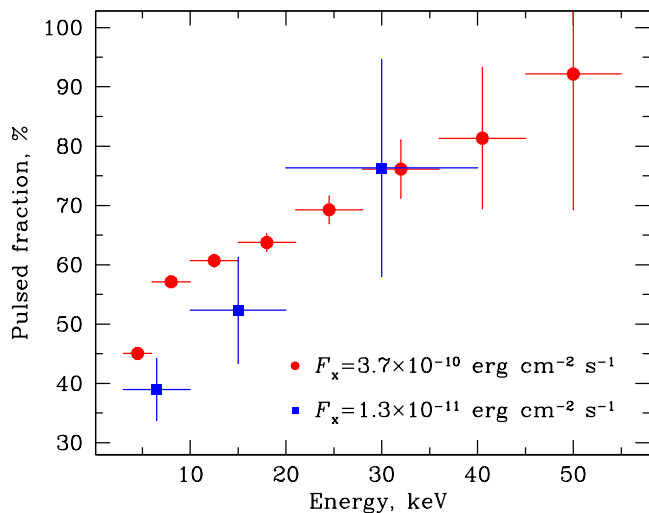


**Fig. 3.** Pulse profiles of MAXI J0903–531 obtained from the *NuSTAR* data in different energy bands. Data for both observations are presented, in black for the low state (ObsID 90701315002) and blue for the high state (ObsID 90701320002). Zero phase was chosen arbitrary to match the minimum in the profile.

ing that pulsar is close to co-rotation at  $\dot{\nu} \leq \dot{M} \sqrt{GM/R_c}$ , where  $R_c = (GM/(2\pi\nu)^2)^{1/3} \sim 10^9$  cm is the co-rotation radius. The resulting value of  $2.6 \times 10^{-7}$  Hz day $^{-1}$  is consistent with our best-fit value, which is also consistent with zero, so we can conclude that quality of available frequency measurements is insufficient to study intrinsic variations of the spin frequency in detail and that the observed spin evolution is dominated by orbital motion. The derived orbital parameters shall, therefore, be only weakly sensitive to assumptions regarding the intrinsic spin variations. The best-fit results are presented in Fig. 2 and Table 2. Note that the reported uncertainties do not account for systematic effects mentioned above and only reflect statistical uncertainties. The combination of the orbital period and eccentricity obtained for MAXI J0903–531 is typical for the Galactic Be/XRPs (e.g. Townsend et al. 2011).

### 3.1.2. Energy dependence of the pulse profiles

Sufficiently high count statistics in the *NuSTAR* data allowed us to study pulse profile shape as a function of energy range and the source luminosity. As can be seen from Fig. 3 the source profile in general is single peaked and depends on energy only slightly. Particularly, at energies below 10 keV it consists of four sub-peaks with increasing domination of one of them at higher energies. This picture is characteristic for both high and low states of the source. At the highest energies (above 40 keV) pulsations are detected only in the brightest observation due to better counting statistics. The pulsed fraction (defined as  $(F_{\text{max}} - F_{\text{min}})/(F_{\text{max}} + F_{\text{min}})$ , where  $F_{\text{max}}$  and  $F_{\text{min}}$  are maximum and minimum fluxes in the pulse profile, respectively) demonstrates an increase from 40% to roughly 80% for both states (see



**Fig. 4.** Dependence of the pulsed fraction of MAXI J0903–531 on energy band based on the *NuSTAR* data in different states of the source.

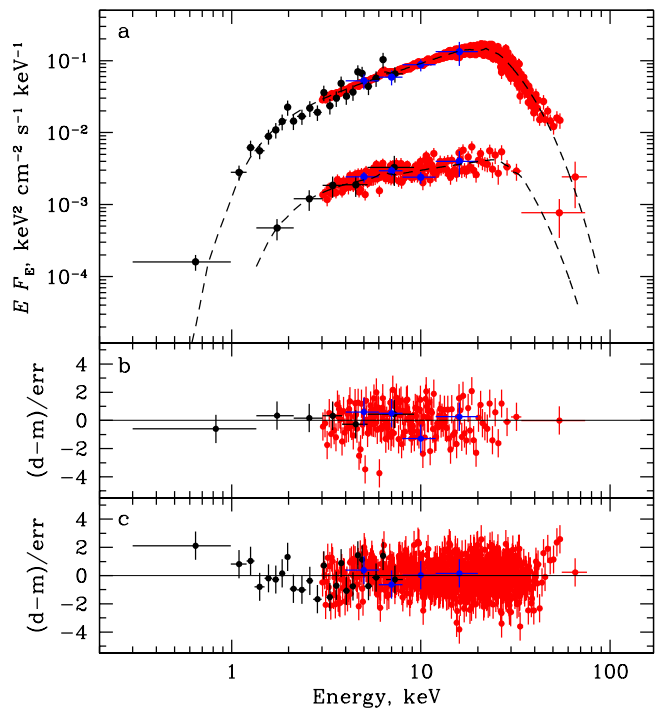
Fig. 4). Such behaviour is typical for the majority of XRPs (Lutovinov & Tsygankov 2009).

### 3.2. Spectral analysis

Spectral properties of MAXI J0903–531 in the low state were studied based on the *NuSTAR* data (ObsID 90701315002) by Thalhammer et al. (2021). The authors showed that the spectrum can be fitted with the model consisting of a simple absorbed cutoff power-law (`CUTOFFPL` in `XSPEC`) with a photon index of  $1.25^{+0.19}_{-0.14}$ ,  $E_{\text{fold}} = 27^{+18}_{-7}$  keV and hydrogen column density fixed at  $N_{\text{H}} = 4.1 \times 10^{21}$  cm $^{-2}$ . To facilitate comparison of the spectra of MAXI J0903–531 in different intensity states, we reanalysed all available data uniformly. To expand our analysis to the lower energies we jointly fitted the *NuSTAR* spectra with the *Swift*/XRT data collected several days apart from the *NuSTAR* observations. Particularly, *NuSTAR* observation 90701315002 was analysed together with XRT observation 00014281005, and *NuSTAR* observation 90701320002 with the XRT observation 00014281006 (see Tab. 1). The data from *Swift*/XRT and *NuSTAR* were used in the 0.3–10 keV and 3–79 keV bands, respectively. Both broadband spectra were also supplemented with the SRG/ART-XC data in the 4–20 keV energy band (ObsIDs 12110050001 and 13000600100, respectively). To fit the data we used the `XSPEC` package (Arnaud 1996) applying W-statistic<sup>4</sup> (Wachter et al. 1979) appropriate for modeling of the background-subtracted spectra in low count regime.

In order to get acceptable description of the source spectrum we used several phenomenological models broadly applied to fit continua of XRP. We started with `CUTOFFPL` modified with a photoelectric absorption model (`TBABS` in `XSPEC`, with abundances from Wilms et al. 2000) and fluorescent emission iron line in the form of additive Gaussian component (`GAU` in `XSPEC`). Although this model fits the spectrum of MAXI J0903–531 in the low state, it is unable to reproduce its spectrum in the high state resulting in the C-stat(d.o.f.)=3345.5(707). Comptonization model (`COMPTT` in `XSPEC`) also produces strong residuals around 10 and 40 keV with resulting C-stat(d.o.f.)=1313.8(707).

<sup>4</sup> <https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSappendixStatistics.html>



**Fig. 5.** Unfolded energy spectra of MAXI J0903–531 in different states with luminosity varying by a factor of  $\sim 30$  (panel a). The black, red and blue points correspond to the *Swift*/XRT, *NuSTAR* and SRG/ART-XC data, respectively. Data from two *NuSTAR* modules are combined for the illustrative purposes only. The dashed lines represent the best-fitting models listed in Table 3. The corresponding residuals for the low and high luminosity states of MAXI J0903–531 are presented at the panels b and c, respectively.

**Table 3.** Best-fitting results of the broad-band spectra approximation for MAXI J0903–531 in different states obtained with *NuSTAR*, *Swift*/XRT and SRG/ART-XC.

Parameter	Low state	High state
$N_{\text{H}}$ , $10^{22}$ cm $^{-2}$	$3.3 \pm 1.1$	$1.3 \pm 0.2$
Phot. index	$1.64 \pm 0.05$	$1.14 \pm 0.01$
$E_{\text{cut}}$ , keV	$28.4^{+4.6}_{-5.1}$	$22.2 \pm 0.3$
$E_{\text{fold}}$ , keV	$7.8^{+6.0}_{-2.3}$	$7.5 \pm 0.2$
$E_{\text{Iron}}$ , keV	$6.29^a$	$6.29 \pm 0.04$
$\sigma_{\text{Iron}}$ , keV	$0.33^a$	$0.33 \pm 0.08$
$Norm_{\text{Iron}}$	$(5.2 \pm 3.8) \times 10^{-6}$	$(1.5 \pm 0.2) \times 10^{-4}$
$C_{\text{XRT}}$	$1.6 \pm 0.3$	$1.05 \pm 0.06$
$C_{\text{FPMA}}$	1	1
$C_{\text{FPMB}}$	$1.03 \pm 0.03$	$1.047 \pm 0.004$
$C_{\text{ART-XC}}$	$0.29 \pm 0.02$	$0.98 \pm 0.05$
$F_{\text{X}}^b$ , $10^{-10}$ erg s $^{-1}$ cm $^{-2}$	$0.129 \pm 0.0006$	$3.73 \pm 0.02$
C-stat (d.o.f.)	404.2 (409)	756.9 (703)

<sup>a</sup> Iron line parameters were fixed at values derived from the spectrum obtained in the bright state.

<sup>b</sup> The observed fluxes given in the 0.5–100 keV energy range.

Finally we were able to get perfect fit using an absorbed power-law model modified with the high-energy exponential

cutoff and iron line ( $\text{TBABS}\times(\text{PO}\times\text{HIGHECUT}+\text{GAU})$ ; see Fig. 5). To get rid of an artificial absorption-like residuals around the cut-off energy  $E_{\text{cut}}$  inherently present in this continuum model due to discontinuity at the cutoff, we also introduced a narrow and shallow ( $\sigma = 0.1E_{\text{cut}}$  keV,  $\tau = 0.1$ ) negative Gaussian with its central energy tied to the cutoff energy (see e.g. Coburn et al. 2002). In order to compare spectra of MAXI J0903–531 in two states, the same model was applied to both broadband data-sets. The resulting parameters of the best-fit model are presented in Table 3. Parameters of the spectral model are typical for the accreting XRPs (e.g. Coburn et al. 2002; Filippova et al. 2005). The absorption value revealed by the fit is just slightly higher in comparison to the Galactic mean value in the direction to the source of  $0.8 \times 10^{22} \text{ cm}^{-2}$  (Willingale et al. 2013) that is typical for the Be/XRPs. Also as can be seen from the residuals in Fig. 5 no significant deviations which can be interpreted as, e.g. a cyclotron resonant scattering feature, can be found in the spectrum.

To verify the conclusion about an absence of additional spectral features appearing only at some specific phases of rotation of the NS, as observed in some XRPs (see e.g. Molkov et al. 2019, 2021), we produced the phase-resolved energy spectra of MAXI J0903–531 using the *NuSTAR* data in the bright state. Particularly, 6 evenly distributed phase bins were chosen as shown in Fig. 6. All spectra were fitted with our best-fit model with iron line energy and width fixed at the values obtained from the averaged spectrum. As can be seen from Fig. 6b hardness of emission is significantly variable over the pulse mainly due to changes of the photon index. We did not find, however, any evidence for any additional emission or absorption features at any phase, nor for significant variations of the  $N_{\text{H}}$  value.

## 4. Discussion

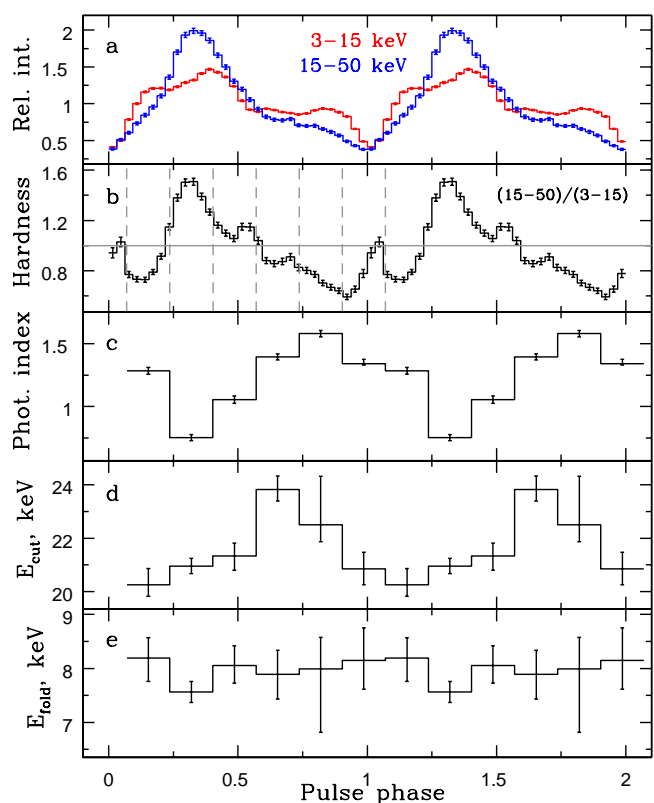
NSs (magnetars and XRPs) are considered as the strongest magnets in the Universe. The only direct way to measure the strength of the magnetic field in such systems is to detect a cyclotron resonant scattering feature in the energy spectrum (see e.g. Staubert et al. 2019). As was discussed in Sec. 3.2, we did not detect any absorption features in the MAXI J0903–531 spectrum. However, the source demonstrates strong flux variability on different time scales. Behaviour of an XRP when it transits from a high accretion rate regime to the quiescence can be used to make some conclusions about the NS magnetic field.

### 4.1. Magnetic field of the NS

It was shown theoretically (Illarionov & Sunyaev 1975) and found observationally for several XRPs (Cui 1997; Tsygankov et al. 2016b,a; Lutovinov et al. 2017) that in the case of fast rotating NS with strong magnetic field the so called propeller effect is expected to stop the accretion abruptly below certain mass accretion rate. This effect takes place when the magnetospheric and corotation radii are about equal. The corresponding luminosity can be estimated as (see, e.g. Campana et al. 2002):

$$L_{\text{prop}} \simeq \frac{GM\dot{M}}{R} \simeq 4 \times 10^{37} k^{7/2} B_{12}^2 P^{-7/3} M_{1.4}^{-2/3} R_6^5 \text{ erg s}^{-1}, \quad (1)$$

where  $\dot{M}$  is the mass-accretion rate,  $B_{12}$  is the NS magnetic field in units  $10^{12}$  G,  $P$  is the NS spin period in seconds,  $M_{1.4}$  is the NS mass in units  $1.4M_{\odot}$  and  $R_6$  is the radius in  $10^6$  cm. The factor  $k$  accounts for the details of interaction of the accretion flow with the magnetosphere, relating its size to the Alfvén radius, that is,



**Fig. 6.** Results of the pulse phase-resolved spectral analysis of MAXI J0903–531 using the *NuSTAR* data in the bright state. To illustrate spectral variations over the pulse phase, the normalised pulse profiles in 3–15 keV and 15–50 keV bands and their ratio are shown in panel a and b, respectively. Panels c, d and e demonstrate behaviour of the photon index, cut-off and folding energies, respectively.

$k = R_{\text{m}}/R_{\text{A}}$ . In the case of disc accretion, it is usually assumed to be  $k = 0.5$  (Ghosh & Lamb 1978).

As can be seen from Eq. (1), the critical luminosity  $L_{\text{prop}}$  is a strong function of the pulsar magnetic field and hence can be used to constrain its value. MAXI J0903–531 does not demonstrate sharp drops of the flux (see Fig. 1) and has hard X-ray spectrum in the quiescent state (with photon index  $1.3 \pm 0.3$  measured from the XRT data averaged over MJD 59405–59423) with luminosity around  $3 \times 10^{34} \text{ erg s}^{-1}$  (assuming distance of 10 kpc and bolometric correction factor of 2). Using this luminosity as an upper limit on the critical luminosity  $L_{\text{prop}}$  we can derive upper limit on the dipole component of the NS magnetic field as  $2 \times 10^{12}$  G assuming standard mass of  $1.4M_{\odot}$  and radius of  $10^6$  cm. Adoption of 12 km radius of the NS would decrease its magnetic field roughly twice. These estimates point to a rather low magnetic field in MAXI J0903–531.

At the same time, the observed stability of the source in the quiescence at around several  $\times 10^{34} \text{ erg s}^{-1}$  evidences the transition of the source to the state of a quasi-stable cold-disc accretion due to the reduced disc viscosity at low mass accretion rates much like in dwarf novae (Tsygankov et al. 2017b). Indeed, transitions to the cold-disc state have been already observed in several XRPs (e.g., Rouco Escorial et al. 2018; Nabizadeh et al. 2019; Tsygankov et al. 2019a; Doroshenko et al. 2020) at luminosities around  $\sim 10^{34-35} \text{ erg s}^{-1}$ . The luminosity corresponding to the transition to this state can be calculated by the equating the inner radius of the accretion disc when temperature there reaches 6500 K to the magnetospheric radius of the NS and,

hence, can be also used to estimate its magnetic field (Tsygankov et al. 2017b). Thus, using eq. (12) from Tsygankov et al. (2017b) and transitional luminosity  $L_{\text{cold}} \sim 3 \times 10^{34} \text{ erg s}^{-1}$ , we obtained magnetic field  $\sim 3 \times 10^{12} \text{ G}$  similar to one obtained above based on the propeller effect.

#### 4.2. Spectral evolution

Deep *NuSTAR* observations of MAXI J0903–531 in two states differ by a factor of  $\sim 30$  in flux allowed us to perform detailed spectral analysis and to compare spectral shape at very different mass accretion rates. The goal of that was to verify an assumption about a strong changes of the spectra in XRP when their luminosity reaches  $\sim 10^{35} \text{ erg s}^{-1}$  as was recently found in several X-ray pulsars (X Persei, Doroshenko et al. 2012; GX 304–1, Tsygankov et al. 2019c; A 0535+262, Tsygankov et al. 2019b; GRO J1008–57, Lutovinov et al. 2021; 2SXPS J075542.5–293353, Doroshenko et al. 2021a; SRGA J124404.1–632232/SRGU J124403.8–632231, Doroshenko et al. 2021b). These spectral changes manifested in the transformation of the classical pulsar-like into a double-hump spectrum were shown to be caused by the Comptonisation of cyclotron photons in the upper over-heated layer of the NS atmosphere (Mushtukov et al. 2021; Sokolova-Lapa et al. 2021). Since in the low state of MAXI J0903–531 it was observed by *NuSTAR* with luminosity of around  $\sim 10^{35} \text{ erg s}^{-1}$ , one can expect to see similar spectral changes in the source.

However, as can be seen from Fig. 5 and Tab. 3 the spectrum of MAXI J0903–531 does not exhibit any dramatic variations and appears to be consistent between the two *NuSTAR* observations. We note that the similarity of X-ray spectra in two luminosity states can be caused by relatively low ( $\lesssim (2-3) \times 10^{12} \text{ G}$ ) magnetic field strength at the surface of a NS. Indeed, the high-energy component observed in low states of some XRP is due to accretion flow braking and subsequent Comptonisation of seed cyclotron photons in the atmosphere of a NS. This component of X-ray spectra appears at around cyclotron energy. In the case of relatively low magnetic field, the high-energy hump of the spectrum arises at lower energy and merges with the low-energy hump caused by thermal radiation of the atmosphere. Additionally, the X-ray radiation leaving the atmosphere of a NS experiences resonant Compton scattering by the infalling material in the accretion channel above the hot spots. Because of a Doppler effect in accretion channel (Mushtukov et al. 2015), the resonant scattering affects X-ray photons from a wide energy range:  $0.6E_{\text{cyc}} \lesssim E \lesssim E_{\text{cyc}}$ . The photons scattered resonantly above the stellar surface experience bulk Comptonisation (Becker & Wolff 2007) and contribute to the high-energy tail of the spectrum. As a result, the resonant bulk Comptonisation together with merged humps in X-ray spectra largely causes the observed spectral shape in XRP at low mass accretion rate. Therefore, we argue that observation of a classical pulsar-like spectrum in the low-luminosity state points to a relatively weak magnetic field of the NS, that in the case of MAXI J0903–531 is supported by our indirect constraints (see Sec. 4.1).

## 5. Conclusion

In this work we presented results of the broadband spectral and timing analysis of emission from the recently discovered transient XRP MAXI J0903–531, obtained with the *NuSTAR*, *Swift*/XRT and SRG/ART-XC instruments at two luminosity states differ by a factor of  $\sim 30$ . The data revealed that the spectrum in both states can be described as a classical pulsar-like

spectrum consisting of power-law with high-energy cutoff. Both phase-averaged and resolved spectra do not contain any absorption components which can be interpreted as a CRSF.

We argue that absence of the transition of the spectrum from typical cutoff power law spectrum to the two-component spectrum at low luminosity observed in other pulsars and, expected also in the case of MAXI J0903–531 in the low state, points to a relatively weak magnetic field of the NS below  $(2-3) \times 10^{12} \text{ G}$ . This value is compatible with the constraints obtained from the propeller effect and transition of the source to the accretion from the cold disc.

Timing analysis of the *NuSTAR* data revealed only slight variations of a single-peaked pulse profile of the source as a function of energy band and mass accretion rate. In both intensity states the pulsed fraction demonstrates increasing from 40% to roughly 80%. We were also able to obtain the orbital solution for the binary system using data from the *Fermi*/GBM, NICER and *NuSTAR* instruments.

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