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# Discovery of a cyclotron absorption line in the transient X-ray pulsar XTE J1829−098

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## ABSTRACT

We report results of a spectral and timing analysis of the X-ray pulsar XTE J1829−098 using data obtained with the *NuSTAR* observatory during an outburst in 2018 August. A strong absorption feature was detected at the energy of $E_{cyc} \simeq 15$ keV in the source spectrum. This feature was interpreted as a cyclotron resonance scattering line corresponding to the magnetic field strength of the neutron star surface $B \simeq 1.7 \times 10^{12}$ G. The pulse phase-resolved spectroscopy shows that the cyclotron line is significantly detected at all phases of the pulse and its energy and other parameters are variable over the pulse period. The timing analysis of the source emission revealed strong pulsations with a period of $P = 7.84480(2)$ s. The pulsed fraction is changed with the energy, including its local increase in the vicinity of the cyclotron line. Using the archival data of the *RXTE* observatory the presence of the cyclotron line in the spectrum of XTE J1829−098 was independently confirmed and tentative hint for the possible anticorrelation of the line energy with the source flux was revealed.

**Key words:** stars: neutron – pulsars: individual (XTE J1829-098) – X-rays: binaries.

## 1 INTRODUCTION

XTE J1829−098 was discovered by the *RXTE* observatory during scans of the Galactic plane in 2004 July. It has been identified as a transient X-ray pulsar with the pulse period of ∼7.8 s (Markwardt, Swank & Smith 2004).

Based on the *XMM–Newton* and *Chandra* data, Halpern & Gotthelf (2007) showed that the spectrum of XTE J1829−098 in soft X-rays (<10 keV) can be described by an absorbed power-law model. It is interesting to note that *XMM–Newton* detected XTE J1829−098 serendipitously on 2003 March (i.e. before its formal discovery) during the Galactic Plane Survey program, whereas *Chandra* observations were performed three times in 2007. Data of the *Chandra* observatory allowed Halpern & Gotthelf (2007) to localize the source with an accuracy of 0.6 arcsec and to determine its infrared counterpart, but the type and class of this star are still unclear. These authors claimed also that the observed X-ray luminosity in the 2–10 keV energy band $L_X \simeq 2 \times 10^{36}(d/10\,\mathrm{kpc})^2\,\mathrm{erg\,s^{-1}}$, where $d$ is the distance to the source, is typical for Be X-ray transients or wind-fed systems.

The flux registered from XTE J1829−098 is variable over the range of more than three orders of magnitude that points to the transient nature of the source. Using a long term light curve of the source from *RXTE*/PCA monitoring observations, Markwardt, Halpern & Swank (2009) estimated an outbursts duration of ∼7 d and an expected recurrence period of ∼246 days. This period can be considered to be a binary period of the system.

New outburst from XTE J1829−098 was detected with the *MAXI* monitor on 2018 August 5 (Nakajima et al. 2018) with the flux of ≃24 mCrab in the 4–10 keV energy band. Immediately after the *MAXI* detection a TOO observation with the *NuSTAR* observatory was triggered with the main purpose to reconstruct the broad-band energy spectrum of the source and to search for the cyclotron line.

In Section 2 we describe observations, which were used in the paper, and the data reduction procedure. Results of the timing analysis, including pulse period measurements and pulse profile studies, are presented in Section 3. In Section 4 we report a discovery of the cyclotron absorption line in the spectrum of XTE J1829−098, results of the pulse phase-resolved spectroscopy and an independent confirmation of the cyclotron line detection from *RXTE* data. Results are summarized and briefly discussed in Section 5.

## 2 OBSERVATIONS AND DATA REDUCTION

Observations of XTE J1829−098 were performed with *NuSTAR* on 2018 August 16 (ObsID 90401332002) with an on-source exposure time of ∼27.8 ks and an average count rate of ∼8 cts s$^{-1}$ per module.

The *NuSTAR* observatory consists of two identical X-ray telescope modules, each equipped with independent mirror systems and focal plane detector units, also referred to as FPMA and FPMB (Harrison et al. 2013). It provides X-ray imaging, spectroscopy and timing in the energy range of 3–79 keV with an angular resolution

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of 18 arcsec (FWHM) and spectral resolution of 400 eV (FWHM) at 10 keV.

To extract spectra and light curves we used the standard NUSTARDAS 1.8.0 software as distributed with the HEASOFT 6.24 package and the CALDB version 20180814. The standard LCMATH tool was used to combine the light curves of the *NuSTAR* modules to improve a statistic for timing analysis. The source data were extracted from a circular region with radius of 130 arcsec, centred at the source position. The background data were extracted using a polygonal region away from the source position. It is important to note that the observational data show no signs of a contamination by a stray-light or ghost rays.

Additionally data of the *RXTE* observatory (Bradt, Rothschild & Swank 1993) were used for an independent analysis and confirmation of the *NuSTAR* detections. The source was observed with *RXTE* in the pointing mode about two dozen times in three epochs: 2004 August (ObsID 90058), 2008 August (ObsID 93445), and 2009 April (ObsID 94419). We used here only data of the Proportional Counter Array (PCA; Jahoda et al. 2006) stored in the STANDARD2 mode.

The obtained spectra were grouped to have more than 20 counts per bin using the `grppha` tool. The final data analysis (timing and spectral) was performed with the HEASOFT 6.24 software package. All uncertainties are quoted at the 1$\sigma$ confidence level, if not stated otherwise.

## 3 SPIN PERIOD AND PULSE PROFILE

The pulse period of the source was determined by using the epoch-folding technique (the `efsearch` tool of the HEASOFT package) we measured the pulse period as $P_{\rm spin} = 7.84480 \pm 0.00002$ s. The uncertainty was defined by the bootstrapping technique (see Boldin, Tsygankov & Lutovinov 2013, for details).

Source light curves in different energy bands were folded into 32 phase bins using the best-fitting spin period value. Corresponding pulse profiles in 3–10 keV, 10–20 keV, 20–40 keV, and 40–79 keV energy bands are shown in Fig. 1. Generally, the pulse profile has a quite smooth and simple shape similar to an asymmetric sin-like one. In the 40–79 keV energy band the photon statistics is quite poor and the pulse profile is dominated mostly by a noise.

The dependence of the pulsed fraction[1] on the energy is presented in Fig. 2. At low energies its value is about 20 per cent with a gradual increase at higher energies that is typical for the majority of X-ray pulsars (Lutovinov & Tsygankov 2009). Besides this general tendency the dependence shows another prominent feature: a local increase of the pulsed fraction up to 30–35 per cent in the energy range of 10–18 keV. Such increases were initially revealed in two brightest transient pulsars V 0332+53 and 4U 0115+63 in the vicinity of the cyclotron line energies and their harmonics (Tsygankov et al. 2006, 2007). Later similar features were also found for a number of other X-ray pulsars (Lutovinov & Tsygankov 2009). Thus, the peculiar increase of the pulsed fraction can be considered as an indication of a possible presence of the cyclotron line at energies 10–18 keV.

[1]The pulsed fraction is defined as PF = $(I_{\rm max} - I_{\rm min})/(I_{\rm max} + I_{\rm min})$, where $I_{\rm max}$ and $I_{\rm min}$ are maximum and minimum intensities in the pulse profile, respectively.

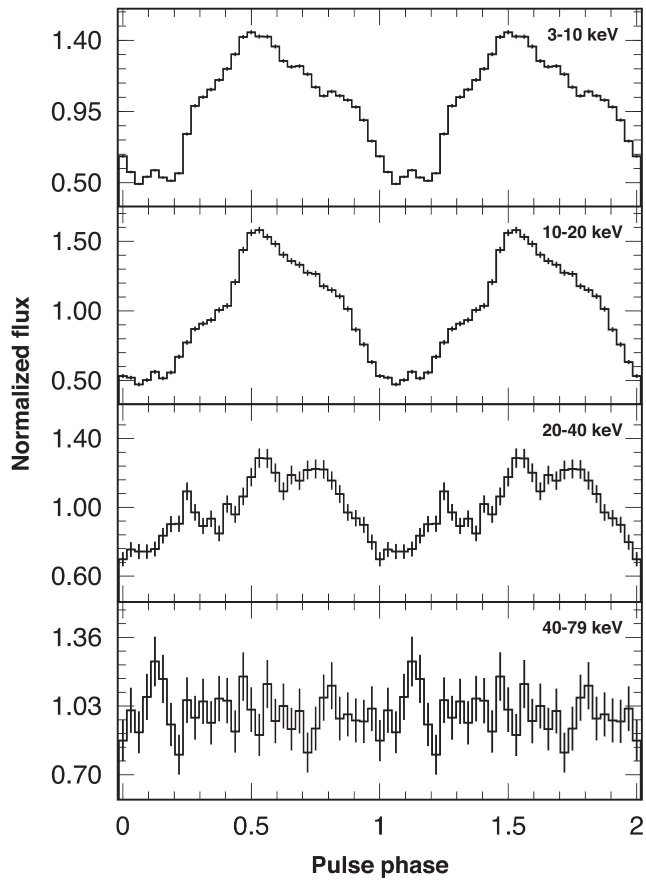


**Figure 1.** Pulse profile of XTE J1829−098 in 3–10 keV, 10–20 keV, 20–40 keV, and 40–79 keV energy bands.

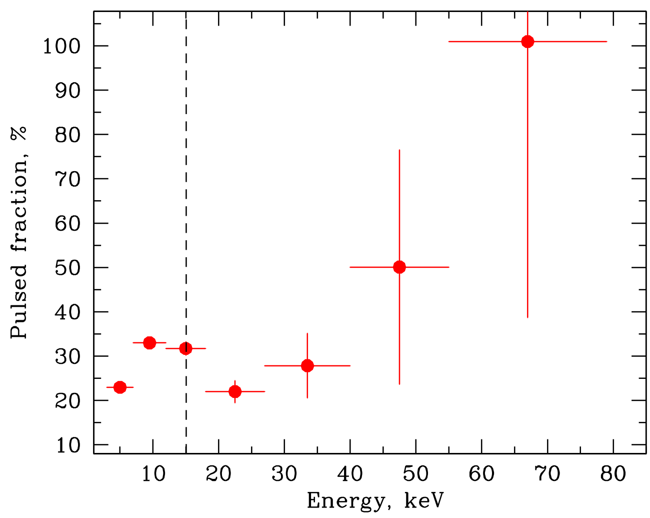


**Figure 2.** Dependence of the pulsed fraction of XTE J1829−098 on the energy. The dashed line shows the position of the cyclotron line found in the source spectrum.

## 4 SPECTRAL ANALYSIS

### 4.1 Phase-averaged spectroscopy with *NuSTAR*

The spectrum of XTE J1829−098 is typical for accreting X-ray pulsars and demonstrates a cut-off at high energies (Fig. 3a). At the



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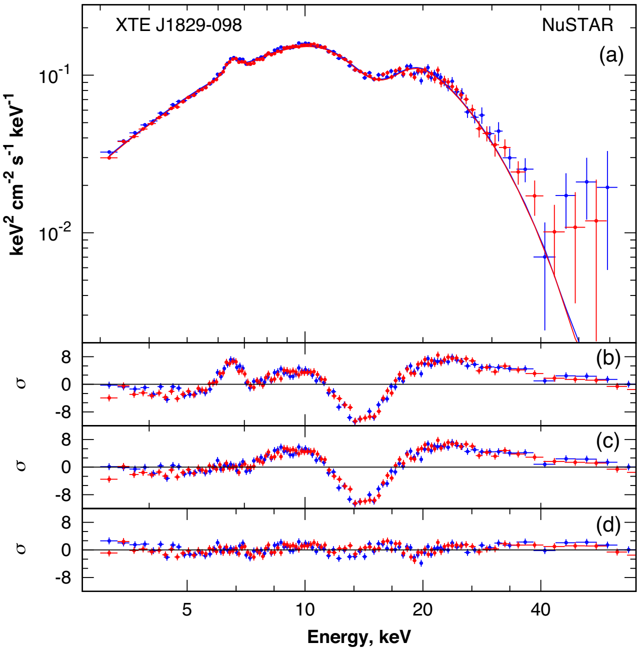


**Figure 3.** Energy spectrum of XTE J1829−098 measured with *NuSTAR* (a): red colour corresponds to the FPMA data, blue one to the FPMB data. Residuals of the models: `cutoffpl` (b), `cutoffpl + gauss` (c), and `cutoffpl*gabs+gauss` (d).

first stage it was approximated with several commonly used models: a power law with an exponential cut-off in the form $E^{-\Gamma}\exp(-E/E_{\rm fold})$ (`cutoffpl` in the XSPEC package), a power law with a high energy cut-off (`powerlaw*highcut` in the XSPEC package) and a thermal Comptonization (`comptt` in the XSPEC package). The source and background spectra from both modules of *NuSTAR* were used for simultaneous fitting. To take into account the uncertainty in the instrument calibrations cross-calibration constant $C$ between them was included in all spectral models.

None of the above mentioned models describe the spectrum well: there are positive deviations of the data at energies 6–7 keV and strong negative deviations at energies 13–18 keV (Fig. 3b). In the following analysis we used the `cutoffpl` model as it describes the spectrum better and has fewer parameters. An addition to the model an iron line at ∼6.4 keV in the Gaussian form improves the fit, but its quality is still non-acceptable ($\chi^2 = 4770$ for 1418 d.o.f.) due to a deficit of photons around 15 keV (Fig. 3c). To describe this feature an absorption component in the form of the `gabs` model was added to the model. It led to a significant improvement of the fit quality ($\chi^2 = 1551$ for 1415 d.o.f., Fig. 3d) and adequate description of the source spectrum.

Thus, the spectrum of XTE J1829−098 can be well approximated by the `cutoffpl` model modified by the emission line, associated with the fluorescent iron line, and the absorption line with the energy of $\simeq$ 15 keV. Best-fitting parameters of this model are summarized in Table 1.

The absorption feature at 15 keV can be interpreted as a possible cyclotron resonant scattering feature. To approximate cyclotron absorption lines two models from the XSPEC package are usually used: `gabs` and `cyclabs`. Both models describe the data adequately well, but the cyclotron line energy derived from the `cyclabs` model is systematically lower than the energy derived from the `gabs` one (see, e.g. Tsygankov, Krivonos & Lutovinov 2012; Lutovinov et al. 2015). If one would use the `cyclabs` model for

**Table 1.** Best-fitting parameters of the XTE J1829−098 spectrum according to the *NuSTAR* data.

| Parameter | Value |
|---|---|
| | Model `cutoffpl*gabs + gauss` |
| $\Gamma$ | $-0.76 \pm 0.02$ |
| $E_{\rm fold}$, keV | $4.45 \pm 0.03$ |
| $E_{\rm cyc}$, keV | $15.05 \pm 0.06$ |
| $W_{\rm cyc}$, keV | $2.26 \pm 0.06$ |
| $\tau_{\rm cyc}$ | $0.52 \pm 0.05$ |
| $E_{\rm Fe}$, keV | $6.50 \pm 0.02$ |
| $\sigma_{\rm Fe}$, keV | $0.24 \pm 0.02$ |
| $N_{\rm Fe}$ | $(2.96 \pm 0.19) \times 10^{-4}$ |
| $C$ | $1.014 \pm 0.003$ |

the description of the XTE J1829−098 spectrum than the cyclotron line energy would be $E_{\rm cyc} \simeq 14.2$ keV.

In spectra of several X-ray pulsars higher harmonics of the cyclotron line are also registered. To examine a presence of higher harmonics in the spectrum of XTE J1829−098 we added to the model an absorption component at the energy corresponding to the double cyclotron line energy; the line width was fixed at the value from Table 1. No further improvement of the fit was found and only an upper limit for the optical depth of the first harmonic of the cyclotron line was obtained as 0.05 (90 per cent confidence level).

An averaged X-ray flux in the 3–79 keV energy band during the *NuSTAR* observation was $F_{\rm x} \simeq 3.6 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ that corresponds to the source luminosity of $L_{\rm x} \simeq 4.3 \times 10^{36}(d/10\ {\rm kpc})^2$ ergs$^{-1}$. Taking into account the spectrum shape it corresponds approximately to the flux measured by Halpern & Gotthelf (2007) in the 2–10 keV energy band.

### 4.2 Pulse phase-resolved spectroscopy

In order to study the evolution of spectral parameters of XTE J1829−098 on the time-scale of the pulse period a pulse phase-resolved spectroscopy was carried out. The pulse period was divided into four intervals and corresponding spectra were extracted from the data. To approximate these spectra we applied the same model that was used for the phase-averaged spectroscopy. As for the phase-averaged spectrum the cyclotron absorption line is detected in all phase bins with the high significance.

An evolution of the line parameters with the pulse phase is shown in Fig. 4. The cyclotron line energy varies significantly (more than 1 keV) over the pulse and approximately correlates with the pulse intensity, reaching values 15.3–15.5 keV at the pulse rise and peak and decreasing down to ∼14.3 keV at the pulse minimum. The cyclotron line width is varied nearly sinusoidally in opposition to the pulse intensity, whereas the line optical depth peaks at the maximum of the line energy. Such variations of line parameters over the pulse are quite usual, observed in many X-ray pulsars and probably connected with changes in the viewing angle to the regions where the cyclotron line is formed (see, e.g. Lutovinov et al. 2015).

### 4.3 Spectroscopy of XTE J1829−098 with *RXTE*

To examine the results obtained with the *NuSTAR* observatory in an independent way and to investigate a possible evolution of the cyclotron line energy with time and the source luminosity we used data from the *RXTE* observatory, which observed XTE J1829−098 many times in 2004–2009.

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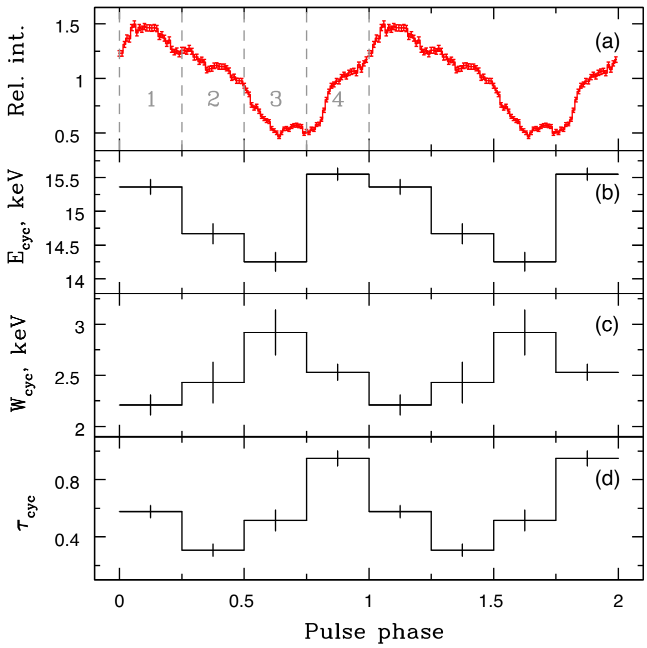


**Figure 4.** Pulse profile of XTE J1829−098 in the 3–79 energy band (a). Variations of the cyclotron line parameters $E_{cyc}$(b), $W_{cyc}$ (c), $\tau_{cyc}$ (d) as a function of the pulse phase (a).

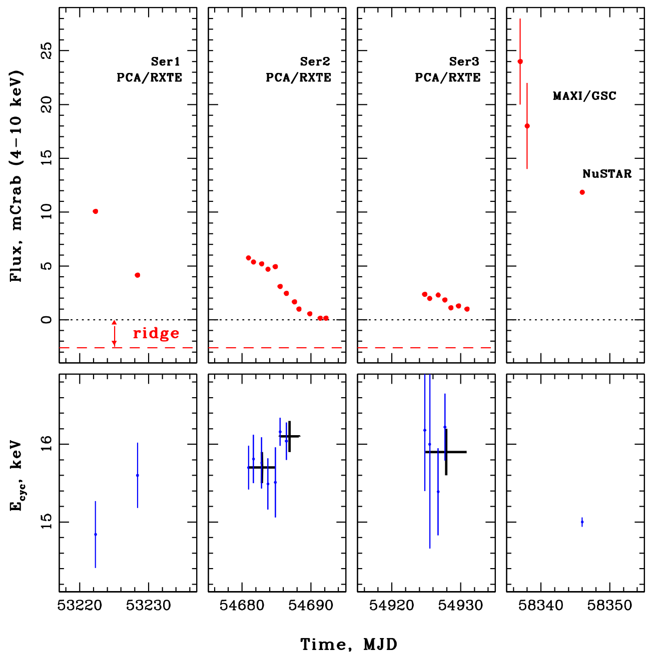


**Figure 5.** Upper panels: Evolution of the XTE J1829−098 flux during four outbursts. Bottom panels: Measured cyclotron line energy in individual observations (blue points) and averaged ones (black crosses).

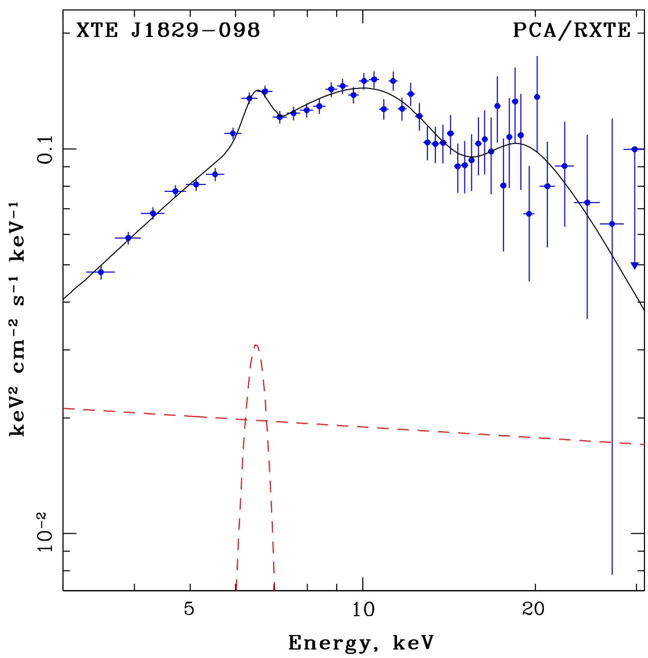


**Figure 6.** The energy spectrum of XTE J1829−098 measured by the *RXTE*/PCA instrument in the brightest state of the source (the first point in Fig. 5). Red dashed lines show a contribution of the Galactic ridge component to the total PCA spectrum (see the text for details). Black solid line represents the best-fitting model for the total spectrum measured with PCA.

The source flux history in the 4–10 keV energy band measured during four outbursts (three were observed with *RXTE*/PCA and one was observed with *MAXI* and *NuSTAR*) is shown on upper panels of Fig. 5. Fluxes, measured by *MAXI* and *NuSTAR*, were taken from Nakajima et al. (2018) and this work, respectively. A correct extraction of the source spectra from the *RXTE* data and calculation of corresponding fluxes meet some peculiarities due to the source location close to the Galactic plane that are described in details in the Appendix.

To approximate the XTE J1829−098 spectra obtained with *RXTE*/PCA we used the same spectral model as for the *NuSTAR* observation. Our analysis revealed that all spectra are well approximated with this model and an inclusion of the absorption component at energies 15–16 keV is required to improve the fit quality in comparison with the simple `cutoffpl` model. Thus we can independently confirm the presence of the cyclotron absorption line in the spectrum of XTE J1829−098. Due to the source faintness and short exposures of *RXTE* observations all three parameters of the cyclotron line cannot be well restricted. Therefore we fixed the line width $W_{cyc}$ on the value determined by *NuSTAR* for the averaged spectrum. Results of measurements of the cyclotron line energy with the *RXTE* observatory are presented in Fig. 5 (bottom panels).

The figure demonstrates that the cyclotron line energy, measured by *RXTE*/PCA and *NuSTAR* in the states with the comparable flux level, is in good agreement. Moreover, there is some tentative hint for the possible anticorrelation of the line energy with the source flux that was observed in several other X-ray pulsars (Tsygankov, Lutovinov & Serber 2010).

## 5 CONCLUSIONS

We report here a discovery of the cyclotron absorption line at $E_{cyc} \simeq 15$ keV in the spectrum of the transient X-ray pulsar XTE J1829−098. Such features are registered in spectra of many X-ray pulsars (see, e.g. Walter et al. 2015; Maitra 2017) and usually used for the direct estimates of the magnetic fields of neutron stars. The measured energy of the cyclotron absorption line corresponds to the magnetic field strength $B \simeq 1.7 \times 10^{12}$ G on the surface of the neutron star.

The pulse phase-resolved spectroscopy showed that parameters of the cyclotron line are variable over the pulse that probably connected

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with changes of the viewing angle to the regions where the cyclotron line is formed.

The pulsed fraction dependence on the energy revealed two distinct features: an overall increase of the pulsed fraction with the energy and its local enhancement at energies 10–18 keV, i.e. near the cyclotron line energy that was observed earlier for several other X-ray pulsars.

Finally, using the archival data of the *RXTE* observatory the presence of the cyclotron line in the spectrum of XTE J1829−098 was independently confirmed. Moreover some hint to the possible anticorrelation of the line energy with the flux was revealed, but for the final conclusions special monitoring observations with the high-sensitivity instruments (like the *NuSTAR* one) are required.

## ACKNOWLEDGEMENTS

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## APPENDIX: XTE J1829−098 SPECTRUM RECONSTRUCTION WITH *RXTE*/PCA

XTE J1829−098 is located in the sky area where the Galactic ridge emission could not be treated as a negligible one for instruments with wide fields of view similar to *RXTE*/PCA. The map of the sky region around XTE J1829−098 in the total PCA energy band is shown in Fig. A1. This image had been reconstructed using all PCA scanning observations of the Galactic plane. An extended emission along the Galactic plane is clearly seen. Thus, to reconstruct correctly the spectrum of XTE J1829−098 we should take into account not only the instrumental background, but also a Galactic ridge emission and the possible contribution of individual sources falling into the PCA FOV (see, e.g. Markwardt et al. 2004). To estimate this 'sky' background component and its spectrum we used two last observations in the Ser. 2 (Fig. 5, upper panels), where XTE J1829−098 was on the undetectable level (i.e. pulsations from the source were not detected). This 'sky' background emission can be adequately fitted by the simple power law model with the spectral index of 2.1, the Gaussian emission line around ∼6.5 keV and the total flux of ≃ 2.5 mCrab in the 4–10 keV energy band. This is well agreed with results of measurements of the Galactic ridge emission by Revnivtsev et al. (2006). The spectrum of the 'sky' background emission and its contribution to the total flux, measured from the XTE J1829−098 with *RXTE*/PCA, are shown by red dashed lines in Figs 5 and 6.

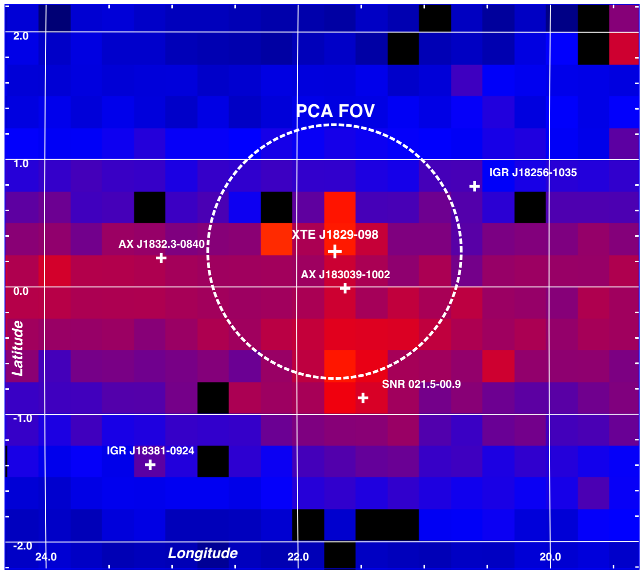


**Figure A1.** The map of the sky around XTE J1829−098, reconstructed with using all Galactic scan observations by *RXTE*. The dashed-line circle (1° in radius) shows the FOV of PCA during pointing observations of XTE J1829-098.

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