Changes in the Nature of the Spectral Continuum and Stability of the Cyclotron Line in the X-ray Pulsar GRO J2058+42

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Abstract—We present the results of our study of the transient X-ray pulsar GRO J2058+42 in a wide energy range in a state with a luminosity $L_x \simeq 2.5 \times 10^{36}$ erg s$^{-1}$. We have found that the pulse profile of the source, along with the pulse fraction, changed significantly in comparison with the previous NuSTAR observations performed when the pulsar was brighter approximately by a factor of 10. The position of the cyclotron line at $\sim 10$ keV in a narrow phase interval is consistent with the observations in the high state. Spectral analysis has shown that at high luminosities $L_x \simeq (2.7 - 3.2) \times 10^{37}$ erg s$^{-1}$ the spectrum has a shape typical of accreting pulsars, whereas a two-component model should be used to describe the spectrum when the luminosity drops approximately by an order of magnitude, to $2.5 \times 10^{36}$ erg s$^{-1}$. This behavior fits into the model in which the low-energy part of the spectrum is formed in a hot spot, while the high-energy one is formed as a result of resonant Compton scattering by the infalling matter in the accretion channel above the neutron star surface.

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INTRODUCTION

The transient X-ray pulsar GRO J2058+42 was first detected during its giant outburst in September 1995 with the BATSE instrument onboard the Compton Gamma-Ray Observatory (Wilson et al. 1995). The type II outburst (bright outbursts in X-ray Be systems that do not depend on the binary orbital phase with a peak luminosity reaching the Eddington limit for a neutron star) lasted about 46 days during which the pulsation period of the flux from the source decreased from 198 to 196 s. The maximum flux from the pulsar during the outburst was $\sim 300$ mCrab in the energy range 20–100 keV. After the main outburst the source had remained active for approximately two years, demonstrating a series of weaker type I bursts (weaker outbursts associated with the binary periastron passage by the neutron star) which had remained active for approximately two years, demonstrating a series of weaker type I bursts (weaker outbursts associated with the binary periastron passage by the neutron star) with a peak luminosity reaching the Eddington limit for a neutron star) lasting about 46 days during which the pulsation period of the flux from the source decreased from 198 to 196 s. The maximum flux from the pulsar during the outburst was $\sim 300$ mCrab in the energy range 20–100 keV. After the main outburst the source had remained active for approximately two years, demonstrating a series of weaker type I bursts (weaker outbursts associated with the binary periastron passage by the neutron star) with a maximum flux of 10–15 mCrab (20–50 keV) and intervals between them $\sim 110$ days, interpreted as the binary orbital period. Small increases in brightness to $\sim 8$ mCrab were also observed between the main outbursts (Wilson et al. 1995). These outbursts were confirmed by the RXTE/ASM instrument and pointed to a possible shorter orbital period of 55 days (Corbet et al. 1997; Wilson et al. 2005).

After this period of activity GRO J2058+42 went into quiescence and exhibited no outburst activity in X-rays until March 22, 2019, when the Burst Alert Telescope (BAT) onboard the Neil Gehrels Swift Observatory (Gehrels et al. 2004) and the Gamma-ray Burst Monitor (GBM) onboard the Fermi Observatory (Meegan et al. 2009) detected a new giant outburst (Bartelmy et al. 2019; Malakaria et al. 2019) with a luminosity peak similar to that of the previous outburst occurred in 1995. During this outburst the source was observed by the Swift, NICER, and Fermi orbital observatories; two observations were also performed by the NuSTAR observatory near the pulsar luminosity peak (Molkov et al. 2019).

The periodic outbursts following the giant outburst suggest that the optical companion in the binary system is a Be star. The optical companion was established more accurately using optical photometry and spectroscopy (Reig et al. 2005) and was...
identified with an O9.5–B0IV–Ve star located at a distance of $9 \pm 1$ kpc. The distance to the binary system, $8^{+0.9}_{-1.2}$ kpc, was refined based on data from the Gaia telescope (Arnason et al. 2021). This value will be used later in the article.

Using the NuSTAR data obtained during the type II outburst in 2019, Molkov et al. (2019) detected a cyclotron absorption line in the source spectrum at $\sim 10$ keV and its two higher harmonics at $\sim 20$ and $\sim 30$ keV, which, however, are recorded only in a narrow range of pulsar rotation phases. These measurements allowed the magnetic field strength of the neutron star in the binary system to be estimated, $\sim 10^{12}$ G. An analysis of the AstroSat data confirmed the presence of the cyclotron line and its two harmonics in the spectrum of GRO J2058+42 (Mukerjee et al. 2020) and significant variations of their parameters with pulsation phase. Furthermore, the authors managed to detect quasi-periodic oscillations at a frequency of 0.09 Hz in the source power spectrum.

To study the properties of the pulsar at low accretion rates (for a review, see, e.g., Tsygankov et al. 2017; the X-ray properties of Be/X-ray pulsars in quiescence), we ordered one more NuSTAR observation, which was carried out approximately 150 days after the maximum of the main outburst. As a result, a flux $F_3 = (3.3^{+0.4}_{-2.8}) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ was recorded from the source in the energy range of 3–79 keV. This value is approximately an order of magnitude lower than the fluxes detected from the source during the first two NuSTAR observations: $F_1 = (3.6 \pm 0.1) \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ and $F_2 = (4.3 \pm 0.1) \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ (Molkov et al. 2019).

This paper is devoted to studying the characteristics of the pulsar in its low state and comparing them with those obtained previously for the bright state.

### OBSERVATIONS AND DATA ANALYSIS

The source GRO J2058+42 in a state with a low luminosity was observed on August 28, 2019, (MJD 58723) with an exposure time of about 38 ks (ObsID 90501336002). To study the spectral and timing characteristics of the pulsar in a wide energy range, the observations were performed simultaneously by the NuSTAR and Swift observatories.

The NuSTAR (Nuclear Spectroscopic Telescope ARray) observatory is sensitive to X-ray emission in the energy range from 3 to 79 keV, recording it with two co-aligned identical X-ray telescopes (FPMA and FPMB) with an energy resolution $\sim 400$ eV at 10 keV (Harrison et al. 2013). The data were processed with the NuSTAR standard processing procedures and standard data analysis software (NuSTARDAS v1.9.7) supplied as part of the HEASOFT v6.29 package with CALDB v20211202 calibrations. The primary data processing was performed with the NUPRODUCTS routine. Subsequently, we used NUPRODUCTS to obtain the energy spectra and light curves of the source. The data of the two modules for the source were extracted from circular regions of radius 50$''$ centered on the source. The background region with the same radius 50$''$ was extracted on the same chip. To compare the properties of the pulsar in states with different intensities, we also used the data from the NuSTAR observation performed on March 25, 2019 (ObsID 90501313002) with an exposure time $\sim 20$ ks (Table 1). The background spectrum was extracted on the adjacent chip, since the source was very bright. Photons from the source and the background were extracted from circular regions of radius 70$''$.

To expand the energy range, we added the spectral data from the observation of GRO J2058+42 carried out by Swift/XRT in the 0.3–10 keV energy range simultaneously with the NuSTAR observation on August 28, 2019 (ObsID 00088982001) with an exposure time of 2 ks. The source spectra were obtained with the online tools (Evans et al. 2009) provided by the UK Swift Science Data Centre at

### Table 1. The observations of GRO J2058+42 used in this paper

| Telescope   | Date                   | ObsID               | Exposure time, ks |
|-------------|------------------------|---------------------|-------------------|
| NuSTAR      | Mar. 25, 2019 (MJD 58567) | 90501313002        | 20                |
| NuSTAR      | Aug. 28, 2019 (MJD 58723) | 90501336002        | 38                |
| Swift/XRT   | Aug. 28, 2019 (MJD 58723) | 00088982001        | 2                 |
Fig. 1. The light curve of the X-ray pulsar GRO J2058+42 in several energy bands obtained with different instruments. The fluxes measured with different instruments are given in different units and renormalized for greater clarity (see the inset). The numbers mark the NuSTAR observations. The scale on the right shows the corresponding luminosity assuming the distance to the system to be 8 kpc. The luminosity is presented in the 1–10 keV energy band to visualize the light curve profile in this picture.

the University of Leicester.¹ We used the Photon Counting (PC) mode data. All energy spectra were binned by 25 counts per bin for our spectral analysis with the $\chi^2$ statistic. The spectra were fitted in the XSPEC v12.12.0 package (Arnaud et al. 1999).

RESULTS

Several observations of GRO J2058+42 performed by the NuSTAR observatory during its outburst activity in 2019 allowed us to carry out a detailed comparative analysis of the timing and spectral properties of the pulsar in states with accretion rates differing approximately by a factor of 10: the luminosity in the bright and low states is $L_x \simeq 2.7 \times 10^{37}$ erg s$^{-1}$ (ObsID 90501313002) and $L_x \simeq 2.5 \times 10^{36}$ erg s$^{-1}$ (ObsID 90501336002), respectively (here and below, the values for the energy range 3–79 keV are used). The light curve obtained with different instruments is shown in Fig. 1.

¹http://www.swift.ac.uk/user\_objects/

Timing Analysis of the Emission from GRO J2058+42

For the timing analysis of the NuSTAR data, the photon arrival times were first corrected for the Solar System barycenter using standard tools from the HEASOFT package. Since there are no well-measured orbital parameters of the binary system, the photon arrival time was not corrected for the orbital motion of the neutron star. All light curves were obtained with a time resolution of 0.1 s, then
the background was subtracted from them, and the light curves of the two modules were combined using the lcmath tool (FTOOLS V6.29). Subsequently, we determined the pulsation period using the epoch-folding technique implemented in the eisearch code from the HEASOFT package, which was 193.375 ± 0.001 s in the low state. The error in the period was estimated using Monte Carlo simulations of the light curve (for details, see Boldin et al. 2013).

In the next step, we extracted the light curves of the source based on the data of both NuSTAR modules in the 3–5, 5–7, 7–9, 9–11, 11–15, 15–19, 19–23, 23–29, 29–41, and 41–79 keV energy ranges. Figure 3 presents the pulse profiles of the source. It can be seen that the pulse profile changes significantly with energy. In the energy range from 3 to ~10 keV the profile exhibits four separate peaks at phases 0.1, 0.3, and 0.6, as in the bright state (see Molkov et al. 2019); a broad peak near phases 0.7–0.9 is also visible in the low state. As the energy increases, the peak at phase 0.3 expands, as in the bright state; the peak at phases 0.7–0.9 persists at all energies up to ~40 keV. At higher energies the secondary peak disappears, which gives rise to a relatively flat segment in the wide phase range 0.5–1.0. This shape of the pulse profile was also observed previously at energies 20–70 keV (Wilson et al. 1998).

We constructed the energy dependence of the pulsed fraction (PF) for both NuSTAR observations used here. The PF was defined as the ratio \((F_{\text{max}} - F_{\text{min}})/(F_{\text{max}} + F_{\text{min}})\), where \(F_{\text{max}}\) and \(F_{\text{min}}\) are the maximum and minimum fluxes in the pulse profile consisting of 20 bins, respectively. According to Fig. 4, the PF for the pulsar in both states increases with energy, which is typical of most X-ray pulsars.
Fig. 3. Pulse profiles of GRO J2058+42 in the low state in ten energy bands based on the NuSTAR data in August 2019. The profiles are shifted along the Y axis for clarity.

(Lutovinov and Tsygankov 2009). However, this increase is nonmonotonic. In particular, in the bright state (red dots) a feature is clearly seen near 10 keV, where the cyclotron absorption line is located. In the low state (blue dots), a break in the dependence is also seen at this energy. No features at the energies corresponding to the higher harmonics of the line are seen due to the insufficient statistics and the large width of the energy channels. It is important to note that such features in the PF near the cyclotron energy were shown to be present previously for a number of X-ray pulsars (Tsygankov et al. 2007, 2010; Lutovinov and Tsygankov 2009; Lutovinov et al. 2017).

Spectral Analysis of the Source GRO J2058+42

To compare the spectral properties of GRO J2058+42 in states with different intensities, we used a continuum model in the form of thermal Comptonization (compTT, Titarchuk 1994), which was applied by Molkov et al. (2019) to describe the spectrum of the source in the bright state. The iron emission line at $\sim 6.4$ keV, whose width was fixed at 0.24 keV determined by Molkov et al. (2019), was also added to the model. The interstellar absorption was taken into account by including the phabs component in the model. The derived absorption $N_H \approx 7 \times 10^{21}$ cm$^{-2}$ agrees well with the Galactic absorption toward the source $\sim 6.2 \times 10^{21}$ cm$^{-2}$ (HI4PI Collaboration, Bekhti et al. 2016). To take into account the different calibrations of the FPMA and FMPB instrument onboard NuSTAR and the nonsimultaneity of the NuSTAR and Swift observations, normalization coefficients were introduced (Table 2); the remaining model parameters for different instruments were fixed between themselves.

In contrast to the data obtained in the bright state, for the low state the PHABS*(GAUSSIAN+COMPTT) model shows an unsatisfactory quality of the fit to the broadband spectrum of GRO J2058+42 with $\chi^2 = 1443.92$ for 1218 degrees of freedom (d.o.f.) and noticeable deviations near $\sim 27$ keV (Fig. 5b). Formally, to describe this feature, a broad absorption line with a Gaussian profile (GABS) may be added to the model. This improved significantly the quality of the fit with $\chi^2 = 1262.05$. 

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Fig. 4. Pulsed fraction for GRO J2058+42 versus energy based on the NuSTAR data for two observations: the green and red colors indicate the dependence in the low (ObsID 90501336002) and bright (ObsID 90501313002) states, respectively; the dashed lines mark the corresponding energies of the cyclotron line and its harmonics.

Previously, Molkov et al. (2019) showed that the phase-resolved spectrum of the source in the bright state at pulse phases 0.05–0.15 contains a cyclotron line at ~10 keV and its harmonics at ~20 and ~30 keV. We also carried out phase-resolved spectroscopy based on the third NuSTAR observation. Just as for the phase-averaged spectrum, we used the PHABS*(GAUSSIAN+COMPTT+COMPTT) model. This model without additional components described adequately all phased spectra, except for the phases 0.05–0.15, whose fit gave an unacceptable value of $\chi^2 = 495.61$ for 406 d.o.f. due to the appearance of a feature near 10 keV (Fig. 6b). To describe this feature, we included an additional gabs component near 10 keV (Fig. 6c), which improved significantly the quality of the fit to $\chi^2 = 451.09$ for 403 d.o.f. (Table 3). Thus, the cyclotron absorption line at ~10 keV was confirmed in the spectrum of the source in the low state at the same phases as in the previous observations. We were unable to register the harmonics at energies of 20 and 30 keV due to the low statistics.

**DISCUSSION**

In this paper we showed that when the luminosity of the X-ray pulsar GRO J2058+42 decreased by a...
few $10^{36}$ erg s$^{-1}$, the energy spectrum of the source changed significantly. In particular, the fit by the thermal Comptonization model (COMPPTT), which works well for the bright state of the pulsar (Molkov et al. 2019), ceased to describe the spectrum. This occurred due to the clear change in the shape of the spectrum expressed in its flattening in the region 10–30 keV. As shown above, an acceptable fit of the spectrum can be obtained by modifying the model by adding either an absorption line at an energy of about 27 keV or a second emission component with a high temperature (COMPPTT+COMPPTT). However, the too large width of the absorption feature and the presence of true cyclotron lines in the phase-resolved spectra of the source at other energies rules out the interpretation of the spectrum flattening through the cyclotron absorption.

The appearance of a second emission component at high energies in low-luminosity pulsars is a firmly established fact (Tsygankov et al. 2019a, 2019b; Lutovinov et al. 2021; Doroshenko et al. 2021). This behavior is associated with the Comptonization of cyclotron photons in the overheated atmosphere of a neutron star (Mushtukov et al. 2021; Sokolova-Lapa et al. 2021). In the case of GRO J2058+42, the cyclotron line is at the lowest energy (∼10 keV) among all of the sources where such a change in the spectrum was observed.

Since the cyclotron line in the spectrum of GRO J2058+42 is observed at ∼10 keV, the high-

| Model parameters | CompTT+GABS | CompTT+CompTT |
|------------------|-------------|---------------|
| $N_{\text{H}}, 10^{22}$ cm$^{-2}$ | 0.2 ± 0.1 | 0.7$^{+0.2}_{-0.2}$ |
| $E_{\text{Fe}}$, keV | 6.4, fixed | 6.32$^{+0.08}_{-0.08}$ |
| $\sigma_{\text{Fe}}$, keV | 0.24 | 0.24, fixed |
| $W_{\text{Fe}}$, keV | 0.03$^{+0.01}_{-0.01}$ | 0.04$^{+0.02}_{-0.01}$ |
| $E_{\text{Cycl}}$, keV | 27.2 ± 0.7 | – |
| $\sigma_{\text{Cycl}}$, keV | 10 ± 2 | – |
| $\tau_{\text{Cycl}}$ | 0.53 ± 0.15 | – |
| $T_{0,\text{CompTT, low}}$, keV | 1.27 ± 0.03 | 1.01$^{+0.05}_{-0.06}$ |
| $kT_{\text{CompTT, low}}$, keV | 10.9 ± 0.7 | 3.9$^{+0.4}_{-0.4}$ |
| $\tau_{\text{CompTT, low}}$ | 3.7 ± 0.4 | 8.0$^{+16.8}_{-1.8}$ |
| $T_{0,\text{CompTT, high}}$, keV | – | $= T_{0,\text{CompTT, low}}$ |
| $kT_{\text{CompTT, high}}$, keV | – | 14.6$^{+1.1}_{-1.2}$ |
| $\tau_{\text{CompTT, high}}$ | – | 2.9$^{+0.9}_{-0.5}$ |
| Flux $\left(3–79$ keV $\right)$, $10^{-10}$ erg cm$^{-2}$ s$^{-1}$ | 3.2$^{+0.1}_{-0.1}$ | 3.3$^{+0.4}_{-2.8}$ |
| $C_{\text{NuSTAR}}$ | 0.99$^{+0.01}_{-0.01}$ | 0.99$^{+0.01}_{-0.01}$ |
| $C_{\text{XRT}}$ | 0.89$^{+0.04}_{-0.04}$ | 0.89$^{+0.04}_{-0.04}$ |
| $\chi^2$ (d.o.f.) | 1262.05 (1216) | 1219.86 (1214) |
energy component of the spectrum cannot be associated with the emission and subsequent Comptonization of cyclotron photons in the hot atmosphere of a neutron star. However, the relatively low cyclotron energy makes a different mechanism for the formation of a high-energy component in the spectrum possible and even necessary. More specifically, in the subcritical accretion regime, which we assume for GRO J2058+42 at the luminosity under consideration, the accretion channel has an optical depth \( < 1 \) with respect to Thomson scattering, but at resonance, where the scattering cross section is much larger than the Thomson one, the accretion channel is optically thick.

The position of the resonance in the reference frame of the neutron star surface is redshifted due to the Doppler effect. The redshift changes depending on the direction of photon escape from the accretion channel, and resonant scattering is expected to cover a wide spectral band from \( \sim 6 \) to \( \sim 10 \) keV. The photons that experienced even a single resonant scattering by the infalling matter, whose velocity is \( \sim 0.5c \), escape from the accretion channel with an energy noticeably higher than that before their scattering, which forms the high-energy part of the spectrum. This mechanism for the formation of the high-energy part of the spectrum suggests a different beam pattern of the emergent radiation of the low-energy and high-energy parts of the spectrum: the high-energy part

Fig. 5. (a) The energy spectrum of GRO J2058+42 measured in August 2019 by NuSTAR (ObsID 90501336002) (green and black dots) and Swift/XRT (red dots), the solid lines indicate the best-fit model; the gray dots indicate the energy spectrum obtained by NuSTAR in March 2019 (ObsID 90501313002). (b) The deviations of the observational data from the PHABS*(GAUSSIAN+COMPTT) model without including other components in the model, (c) for the PHABS*(GAUSSIAN+COMPTT)*GABS model, and (d) the deviations of the observational data from the PHABS*(GAUSSIAN+COMPTT+COMPTT) model.
Fig. 6. (a) The energy spectrum of GRO J2058+42 at pulse phases 0.05–0.15 for the NuSTAR observation in August 2019 (ObsID 90501336002). The data of both FPMA and FPMB modules are indicated by the blue and black dots. The solid blue line indicates the best-fit model, while the black and green lines indicate the contribution of different components. (b) The deviations of the observational data from the PHABS*(GAUSSIAN+COMPTT+COMPTT) model similar to the average spectrum model, (c) for the model with the cyclotron line PHABS*(GAUSSIAN+COMPTT+COMPTT)*GABS.

of the spectrum, being the result of scattering in the accretion channel, must have a beam pattern close to the fan-shaped one. The observed evolution of the pulse profile with photon energy is probably associated with this difference in the beam patterns at high and low energies (Fig. 3) (Mushtukov et al. 2018).

CONCLUSIONS

In this paper we presented the results of our timing and spectral analysis of the source GRO J2058+42 in a wide energy range whose data were obtained by the NuSTAR and Swift observatories in August 2019. According to these results, the source was in a state with a low luminosity $L_x \simeq 2.5 \times 10^{36}$ erg s$^{-1}$, which is an order of magnitude lower than the previously observed ones (Molkov et al. 2019). We showed that the energy spectrum changed greatly when passing to a low accretion rate. To describe the spectrum, we proposed a continuum model consisting of two Comptonization components, CompTT+CompTT. The observed shape of the spectrum in the low state can be interpreted in terms of the model where the low-energy part of the spectrum is formed in a hot spot, while the high-energy one is formed as a result of resonant Compton scattering of photons in the range 6–10 keV by the infalling matter in the accretion channel above the neutron star surface.

We performed phase-resolved spectroscopy that showed a deficit of photons near 10 keV in the pulse phase range 0.05–0.15. This feature can be interpreted as a cyclotron absorption line. The position of the cyclotron line at $\sim 10$ keV in a narrow phase interval is consistent with the observations of the source in the high state (Molkov et al. 2019).

Our timing analysis showed changes in the energy-averaged pulse profile in comparison with the bright state. The PF has the form of an increasing dependence on energy typical of X-ray pulsars. At the same time, it points to the presence of a feature near the cyclotron energy in both low and bright states.
Table 3. Parameters of the phased spectrum at 0.05–0.15 for GRO J2058+42 with the continuum described by the \texttt{CONSTANTA*PHABS*(GAUSSIAN+COMPTT+COMPTT*)GABS} model

| Model parameters          | Values                          |
|---------------------------|---------------------------------|
| $N_H$, 10$^{22}$ cm$^{-2}$| 0.7, fixed                      |
| $E_{Fe}$, keV             | 6.32, fixed                     |
| $\sigma_{Fe}$, keV        | 0.24, fixed                     |
| $W_{Fe}$, keV             | $0.08^{+0.04}_{-0.04}$          |
| $E_{Cycl}$, keV           | $10.6^{+0.2}_{-0.2}$            |
| $\sigma_{Cycl}$, keV      | $1.3^{+0.3}_{-0.2}$             |
| $\tau_{Cycl}$             | $0.31^{+0.03}_{-0.02}$          |
| $T_0$, Comptt, low, keV   | 1.01, fixed                     |
| $kT_{Comptt}$, low, keV   | $4.9^{+0.7}_{-0.5}$             |
| $\tau_{Comptt}$, low      | $4.8^{+0.6}_{-0.5}$             |
| $T_0$, Comptt, high, keV  | = $T_0$, Comptt, low            |
| $kT_{Comptt}$, high, keV  | $14.5^{+2.3}_{-1.6}$            |
| $\tau_{Comptt}$, high     | $>15$                           |
| $C_{NuSTAR}$              | $0.98^{+0.02}_{-0.02}$          |
| $\chi^2$ (d.o.f.)         | 336.49 (362)                    |

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