ON TIMING AND SPECTRAL CHARACTERISTICS OF THE X-RAY PULSAR 4U 0115+63: EVOLUTION OF THE PULSATION PERIOD AND THE CYCLOTRON LINE ENERGY

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An overview of the results of observations for the transient X-ray pulsar 4U 0115+63, a member of a binary system with a Be star, since its discovery to the present day (~40 years) based on data from more than dozen observatories and instruments is presented. A overall light curve and the history of change in the spin frequency of the neutron star over the entire history of its observations, which also includes the results of recent measurements made by the INTEGRAL observatory during the 2004, 2008, and 2011 outbursts, are provided. The source’s energy spectra have also been constructed from the INTEGRAL data obtained during the 2011 outburst for a dynamic range of its luminosities ($10^{37} - 7 \times 10^{37}$ erg s$^{-1}$). We show that apart from the fundamental harmonic of the cyclotron absorption line at energy $\sim 11$ keV, its four higher harmonics at energies $\simeq 24, 35.6, 48.8, \text{ and } 60.7$ keV are detected in the spectrum. We have performed a detailed analysis of the source’s spectra in the 4-28 keV energy band based on all of the available RXTE archival data obtained during bright outbursts in 1995–2011. We have confirmed that modifying the source’s continuum model can lead to the disappearance of the observed anticorrelation between the energy of the fundamental harmonic of the cyclotron absorption line and the source’s luminosity. Thus, the question about the evolution of the cyclotron absorption line energy with the luminosity of the X-ray pulsar 4U 0115+63 remains open and a physically justified radiation model for X-ray pulsars is needed to answer it.

INTRODUCTION

The X-ray pulsar 4U 0115+63 has a long history of observations and is well suited for testing models for the evolution of binary systems, models for the structure and evolution of decretion disks around Be stars, and models for the structure of emitting regions (accretion columns) in neutron stars. The source was discovered in the UHURU satellite survey (Giacconi et al., 1972; Forman et al., 1978). Later on, this object was found in the Vela-5B satellite archival data since 1969 (Whitlock et al., 1989). Accurate measurements of its position in the sky were subsequently made by the SAS-3, Ariel-V, and HEAO-1 observatories (Cominsky et al., 1978; Johnston et al., 1978). These measurements allowed the optical component in this binary system to be determined; it turned out to be a Be star called V635 Cas (Kholopov et al., 1981) with an apparent magnitude $V \approx 15.5$ and strong reddening (Johns et al., 1978; Hutchings & Crampton, 1981). A typical Be star is a hot ($T > 10000$ K), massive ($M > 5 M_\odot$) O- or B-type star with strong Balmer emission lines detected in its spectrum. These lines originate in the material outflowing from the star that forms the so-called decretion equatorial disk (Slettebak, 1988; Reig, 2011). This outflow of material is caused by a high rotational velocity and a high light pressure on the surface of the Be star. The distance to the system 4U 0115+63/V635 Cas is estimated to be $\approx 7$ kpc (Negueruela & Okazaki, 2001). The orbital parameters of the binary system were determined from SAS-3 observations: the orbital period is $\approx 24.3$ days, the eccentricity is

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The source being studied is the first X-ray transient with a Be companion in the energy spectrum of which an absorption line was detected at energy 20 keV \cite{Wheaton:1979}. HEAO-1 A4 subsequently, it was interpreted as the first harmonic of the fundamental cyclotron absorption line at energy $\approx 11.5$ keV \cite{White:1983}. At present, 4U 0115+63 is the only X-ray pulsar in the spectrum of which four harmonics of the cyclotron absorption line, along with the fundamental one, have been detected. In addition, an anticorrelation between the position of the cyclotron absorption line and the source's intrinsic luminosity was recorded with confidence for two bright transient pulsars (4U 0115+63 and V 0332+53). Such a dependence is observed both on long timescales (see, e.g., Mihara et al. 2004; Nakajima et al. 2006, 2010; Mowlavi et al. 2006; Tsygankov et al. 2006, 2007, 2010) and for variability on the scale of the pulsation period \cite{Klochkov:2011}. Such a behavior can be explained in general terms within the classical model of accretion column change with luminosity \cite{Basko:Sunyaev:1976}, which has been further developed recently by \cite{Poutanen:2013}. Since data on the behavior of the cyclotron line energy allow accretion column models to be tested, their accurate measurement is an important task.

Here, we provide a complete historical overview of the light curves and pulse period for 4U 0115+63 and present new results for the 2004, 2008, and 2011 outbursts obtained from INTEGRAL data. In addition, we continue the study and interpretation of the behavior of the cyclotron absorption line as the source's luminosity changes begun by \cite{Burnard:1991}; Mihara et al. 2004; Nakajima et al. 2006, 2007, 2010) and for\cite{Mowlavi:2010} both on long timescales (see, e.g., Mihara et al. 2004, 2006; Tsygankov et al. 2007; Li et al. 2012; Müller et al. 2013). We discuss the luminosity – fundamental cyclotron line harmonic energy anticorrelation and show that the latter depends on the chosen model spectrum and, for a certain shape of the continuum, the line energy is practically constant. In addition, based on the INTEGRAL data obtained during the 2011 outburst, we have constructed broadband spectra of the source for various luminosity levels in which, apart from the fundamental harmonic, four more higher harmonics of the cyclotron absorption line are detected.

**OBSERVATIONS AND DATA ANALYSIS**

To construct the light curve and the evolution of the pulsation period for the X-ray pulsar 4U
0115+63, we processed the observational data from more than dozen observatories and instruments that have operated or are operating in orbit from 1969 to the present days. In particular: the Vela-5B satellite data were taken from the HEASARC (High Energy Astrophysics Science Archive Research Center) open archive; the UHURU, Ariel-V, and GINGA satellite data were digitized from the papers listed below (see the Section “Light Curves and Evolution of the Pulsation Frequency”); the GRANAT satellite data were retrieved from the archive of the Department of High-Energy Astrophysics at the Space Research Institute of the Russian Academy of Sciences; the BATSE data (fluxes and pulsation frequencies) were digitized from papers, except the February-March 1999 outburst whose data are available in the BATSE archives; the RXTE/ASM data were taken from the official site of the ASM/RXTE development team; the team of the Swift/BAT all-sky monitor provides archival data and a list of transients via the corresponding website; the MAXI monitor data were taken from the official site. The INTEGRAL observatory (Winkler et al., 2003) performed series of observations for the X-ray pulsar 4U 0115+63 during the 2004 (Tsygankov et al., 2005), 2008 (Li et al., 2012), and 2011 outbursts. The results of our timing analysis of these data were also used to construct the light curve and the evolution of the pulsation period. The OSA-10 standard software was used for processing the JEM-X data and for our timing analysis of the data from the ISGRI detector of the IBIS telescope. The software developed at the Space Research Institute of the Russian Academy of Sciences (Krivonos et al., 2010) was used to construct the light curves and spectra from ISGRI/IBIS data. Here, we also analyzed the data from all RXTE observations of 4U 0115+63 (Bradt et al., 1993). In particular, we used the PCA data obtained during the 1999, 2000, 2004, 2008, and 2011 outbursts for our spectral analysis. The standard set of programs from the FTOOLS version 6.12 package was used for the RXTE data processing and the final analysis of all the remaining observations.

RESULTS OF TIMING ANALYSIS

Light Curves and Evolution of the Pulsation Frequency

Our investigation was naturally begun with a study of the light curves for 4U 0115+63 based on the observational data from X-ray monitors and observatories over the last 40 years, from the Vela-5B archival data to the MAXI and Swift/BAT data (see Table 1). Figure 1 presents a complete historical light curve of the X-ray pulsar 4U 0115+63; Fig. 2 (upper panels) presents the same light curves but with a better time resolution. Since the observations were carried out with different instruments in different energy bands, to present a uniform light curve, the results of these observations were recalculated to the 3-100 keV energy band as follows: the flux measured from the pulsar 4U 0115+63 in the instrument’s band is known from the observations; given the shape of the pulsar’s spectrum and assuming it to be constant, we can find the flux from the source in the energy band of interest normalized to the Crab flux in the same energy band. To recalculate the fluxes, we took the spectral shape for 4U 0115+63 in the form of a power law with a high-energy cutoff typical of X-ray pulsars (White et al., 1983):

\[ f(E) = AE^{-\Gamma} \times \begin{cases} \frac{1}{\exp\left(\frac{E - E_{\text{cut}}}{E_{\text{fold}}}\right)} & (E \leq E_{\text{cut}}) \\ \exp\left(\frac{E - E_{\text{cut}}}{E_{\text{fold}}}\right) & (E > E_{\text{cut}}) \end{cases} \]

with parameters \( E_{\text{cut}} = E_{\text{fold}} = 8 \) keV and \( \Gamma = 0.1 \). Thus, all of the fluxes given below refer to the 3-100 keV energy band, unless stated otherwise.

To make Figs. 1 and 2 more demonstrable, we cleaned the light curves of the measurements where the flux did not exceed its measurement error and omitted the flux measurement errors themselves. The lower panels in Fig. 2 present the evolution of the neutron star spin frequency in which its increase (spin-up of the neutron star) over the entire history of the source’s observations is clearly traceable. A correlation between the outbursts and the increase in neutron star spin frequency can also be seen. This spin-up of the neutron star is related to the positive angular momentum transferred by the infalling material from the accretion disk (see, e.g., Ghosh & Lamb, 1979). It can also be clearly seen that the neutron star spins down between the outbursts. This may suggest that the neutron star magnetosphere interacts with the surrounding material from the stellar wind of the Be star, for example, through the propeller mechanism (Illarionov & Sunyaev, 1973; Shakura, 1973). For

\(^{1}\)http://www.batse.msfc.nasa.gov/batse/pulsar/data/
\(^{2}\)http://xte.mit.edu/asmlc/ASM.html
\(^{3}\)http://swift.gsfc.nasa.gov/docs/swift/results/transients/
\(^{4}\)http://maxi.riken.jp/top/index.php?cid=1&disp_mode=source
\(^{5}\)http://isdc.unige.ch
Table 1. Known significant outbursts of the X-ray transient pulsar 4U 0115+63 since its discovery to the present day as revealed by the listed observatories and instruments. The first column gives the corresponding parts of Fig. 2, where the outburst light curves and pulsation frequencies are presented. For details, see the text.

| Date            | Begin MJD | End MJD | $P_{\text{orb}, 100\text{keV}}$ | Instruments                  | References |
|-----------------|-----------|---------|--------------------------------|------------------------------|------------|
| (a) 1969-1971²  | ~40000    | ~41000  | 1.0                           | Vela 5B, UHURU               | 1, 2       |
| August 1974     | 42265     | 42295   | >1.5                          | Vela 5B                      | 2          |
| December 1977   | 43500     | 43550   | >1.0                          | Vela-5B, SAS-3, Ariel-V, HEAO-1 | 2, 3, 4, 5 |
| December 1980   | 44589     | >0.2    |                                |                              | 6          |
| February-March 1987 | 46835    | 46865   | 0.2                            | GINGA                        | 7          |
| April-May 1991  | 48360     | 48375   | 0.07³                         | BATSE                        | 8, 9       |
| May-June 1994   | 49480     | 49530   | 0.13³                         | BATSE                        | 10         |
| November-December 1995 | 50040   | 50090   | 0.7 (0.14³)                   | BATSE, GRANAT               | 10, 11, 12 |
| (g) August-November 1996² | ~50250 | ~50500  | 0.1                            | RXTE/ASM                     |            |
| (h) February-March 1999 | 51230   | 51280   | 0.6 (0.2³)                     | RXTE/ASM,⁴                  | 13         |
| (i) September-October 2000 | 51780   | 51830   | 0.4                            | RXTE/ASM⁴                   |            |
| (j) September-October 2004 | 53240   | 53300   | 0.6                            | RXTE/ASM⁴, INTEGRAL⁵          |            |
| (k) March-April 2008 | 54530   | 54580   | 0.5                            | RXTE/ASM⁴, Swift/BAT⁶, INTEGRAL⁵ |            |
| (l) May-June 2011 | 55720   | 55755   | ~0.8                           | RXTE/ASM⁴, MAXI, Swift/BAT⁶, INTEGRAL⁵ |            |

1 (1) Giacconi et al. (1972) (2) Whitlock et al. (1989) (3) Cominsky et al. (1978) (4) Rose et al. (1979) (5) Johns et al. (1978) (6) Ricketts et al. (1981) (7) Tsunemi & Kitamoto (1988) (8) Cominsky et al. (1994) (9) Bildsten et al. (1997) (10) Wilson et al. (1994) (11) Finger et al. (1995) (12) Sazonov & Sunyaev (1995) (13) Wilson et al. (1999)

2 Series of type I outbursts.
3 Pulsed flux.
4 Data were provided by the RXTE/ASM.
5 This paper.
6 Data were provided by the Swift/BAT.

Table 2. History of orbital period measurements for 4U 0115+63

| T, MJD    | $P_{\text{orb}}$, days | Observatory | Reference    |
|-----------|------------------------|-------------|--------------|
| 40963.81 ± 0.40 | 24.3149 ± 0.0044     | UHURU       | Kelley et al. (1981) |
| 43540.951 ± 0.006 | 24.309 ± 0.021      | SAS-3       | Rappaport et al. (1978) |
| 44589     | 24.3155 ± 0.0002     | Ariel 6     | Ricketts et al. (1981) |
| 47942.224 ± 0.004 | 24.31643 ± 0.00007  | GRANAT      | Lutovinov et al. (2000) |
| 49279.267 ± 0.0034 | 24.317037 ± 0.000062 | BATSE       | Bildsten et al. (1997) |
| 53243.038 ± 0.051 | 24.3174 ± 0.0004    | RXTE        | Raichur & Paul (2010)  |

Astronomy Letters | vol 39 | N6 | 2013
a clear demonstration of the described effects, the dashed lines in the lower panels of Fig. 2 indicate
the last known neutron star spin frequency before the onset of an outburst. It is also interesting to
note the neutron star continues to slow down for some time at the onset of many outbursts and only
then does it begin to speed up.

As has been said above, the X-ray pulsar 4U 0115+63 was discovered by the Uhuru (2-6 keV) satellite
during its type I outburst with a peak flux of 0.2 Crab (2-6 keV) and was initially named 2U 0115+63. Subsequently, this object was
found in the Vela-5B archival data, where several type I outbursts were detected (August 1969, January 1970, August 1970, January 1971; Fig. 2a, Whitlock et al. (1989)). Thereafter, the type I activity essentially ceased and, starting from the
outburst in January 1971 (Whitlock et al. 1989), 4U 0115+63 has exhibited mainly the type II
activity, giant outbursts with a recurrence period of about three years (Fig. 1). The outburst in August 1974 was detected only by the Vela-5B satellite. We took the spin frequencies calculated from Uhuru data from Ricketts et al. (1981)and Kelley et al. (1981) and those calculated from Vela-5B data from Whitlock et al. (1989) (indicated by the diamonds in the lower panel of Fig. 2a).

The outburst in December 1977-January 1978 was detected by the instruments of the SAS-3 (Cominsky et al. 1978), Ariel-V (Rose et al. 1979), and HEAO-1 (Johns et al. 1978) observatories. Rose et al. (1979) investigated
phase-resolved spectral characteristics and showed them to change greatly with pulse phase. The pulsation frequency determined by Ricketts et al. (1981) from SAS-3 observations is indicated by the diamond in the lower panel of Fig. 2b. The outburst with an intensity of 0.2 Crab (3-6 keV) in December 1980 was detected only by the Ariel-VI satellite (Ricketts et al. 1981). The orbital parameters calculated from these observations allowed the mass of the Be star to be constrained, $M_e \lesssim 25 M_\odot$. No outbursts were detected from 1980 to 1987 probably because there were no suitable X-ray monitors in orbit at this time.

The next small (with an intensity up to 0.18 Crab) outburst was detected by the ASM instrument (1-20 keV energy band) of the GINGA telescope in February-March 1987 (Tsunemi & Kitamoto 1988). These observations confirmed the ~ 3-year periodicity of outbursts. The outburst in February 1990 (Fig. 2c) with a peak flux of about 0.4 Crab (1-20 keV) was also observed by the GINGA satellite (Makino et al. 1990). The apsidal motion in the system $\dot{\omega} = 0.0703 \pm 0.0016 \text{ yr}^{-1}$ was determined from these data (Tamura et al. 1992). In addition, observations with the LAC instrument of the GINGA observatory allowed one to study the source’s spectra in the 1-37 keV energy band and to detect two absorption lines at energies $\approx 12.5$ and $\approx 22.6$ keV. This confirmed the previous conclusion about the simultaneous presence of two cyclotron absorption line harmonics in the pulsar spectrum. Concurrently with the GINGA satellite, a series of observations was performed for the source with the ART-P (3-30 keV) telescope of the GRANAT observatory on February 18, 19, and 22, 1990 (Gilfanov et al. 1991, Lutovinov et al. 1994). These observations allowed one to refine the epoch of periastron passage, $\tau (\text{MJD}) = 47942.224 \pm 0.004$ and to measure the orbital period of the binary system, $P_{\text{orb}} = 24.31643 \pm 0.00007$ days. Two cyclotron absorption lines at energies $\approx 12.10$ and $\approx 22.24$ keV were also detected in the spectra of the pulsar 4U 0115+63 (Lutovinov et al. 2000). The measured period of the pulsar was $P = 3.61461 \pm 0.00001$ (indicated by the diamond in the lower panel of Fig. 2c).

The small outburst in April-May 1991 was detected by the BATSE instrument (Cominsky et al. 1994; Bildsten et al. 1997) onboard the Compton-GRO observatory. The peak pulsed flux during the outburst was 0.07 Crab (20-50 keV) and its duration was about 10 days (see Fig. 2d).

The outburst in May-June 1994 with a duration of 50 days and a peak pulsed flux of 0.13 Crab and the outburst in November-December 1995 with a duration of 30 days and a peak pulsed flux of 0.14 Crab were also detected only by the BATSE instrument (Wilson et al. 1994; see Figs. 2e and 2f, respectively). The spin period of the neutron star and its evolution presented in the lower panels of these figures were determined from these data (Bildsten et al. 1997). The outburst in November 1995 was also detected by the GRANAT/WATCH instrument with a peak flux of 0.7 Crab in the 8-20 keV energy band (Sazonov & Sunyaev 1995).

Shortly after the launch of the RXTE observatory in December 1995, the All-Sky Monitor (ASM) (the operating energy range 1.3-12 keV) detected a series of weak type I outbursts from August to November 1996 (Fig. 2g). The peak flux during these outbursts was 0.1 Crab in the instrument’s band. The pulsation frequency determined from Compton GRO data was 276.667 mHz (Scott et al. 1996, indicated by the diamond in the lower panel.
The outburst in February-March 1999 with a peak flux of 0.8 Crab (1.3–12 keV) was detected by both RXTE/ASM and BATSE with a pulsed flux of 0.2 Crab in the 20–50 keV energy band. The outburst lasted for about 50 days (see Fig. 2h). The next outburst in September-October 2000 was already observed solely by RXTE/ASM; the peak flux was about 0.38 Crab (1.3–12 keV) and the duration was 40 days (Fig. 2i).

In September 2004, the onset of another outburst was recorded by the INTEGRAL observatory (Lutovinov et al. 2004). Subsequently, the outburst was observed with the instruments of the RXTE and INTEGRAL observatories with a peak flux of 0.5 Crab in the 20–60 keV energy band. Variations of the neutron star spin frequency during the outburst were determined from INTEGRAL data. The results of these measurements are presented in the lower panel of Fig. 2l, along with those from RXTE data (Raichur & Paul, 2010, indicated by the diamond). With the launch of the Swift observatory in 2004, an all-sky monitoring in hard X-rays became possible and the succeeding 4U 0115+63 outbursts were detected already in a wide energy range. In particular, the peak fluxes recorded during the outburst in March-April 2008 were 0.4 Crab for RXTE/ASM and 0.6 Crab for Swift/BAT (15–50 keV). At the same time, INTEGRAL observations of the pulsar 4U 0115+63 were performed. They allowed the spin period of the neutron star to be determined (see Fig. 2k, the lower panel).

The last known outburst from 4U 0115+63 occurred in May-June 2011 and was observed by the Swift/BAT and INTEGRAL observatories as well as by the MAXI (2–20 keV) monitor. The peak flux during the outburst was ≃ 0.4 Crab from Swift/BAT data and ≃ 1.0 Crab from MAXI data in the corresponding bands of the instruments. The observations performed with the INTEGRAL telescopes at our request allowed the spin frequency of the neutron star to be measured; the results of these measurements are shown in the lower panel of Fig. 2l. It also shows the evolution of the neutron star spin frequency during the outburst determined using data from the Gamma-ray Burst Monitor (GBM) of the Fermi observatory.

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6Fermi/GBM, http://f64.nsstc.nasa.gov/gbm/

Astronomy Letters vol 39 №6 2013

**Determination of the Pulse Period from INTEGRAL data**

The spin frequencies of the neutron star in the system 4U 0115+63/V635 Cas determined here from INTEGRAL data are shown in the lower panels of Figs. 2j-2l. The spin frequencies and their errors were calculated as follows. After the correction to the barycenters of the Solar system and the binary system, each light curve was analyzed by the epoch folding technique (Leahy et al. 1983). The derived $P-\chi^2$ relationship was then fitted by a Gaussian. In this way, the pulsation period was determined for the original light curve. The errors in the period were estimated for each light curve by the so-called bootstrap method (for a brief description, see Lutovinov et al. 2012). First, we generated the light curves in which the count rate at each instant of time was determined from the formula $r'_i = r_i + \gamma\sigma_i$, where $r'_i$, $r_i$, and $\sigma_i$ are the count rate at the $i$th point of the new light curve, the same for the original light curve, and the measurement error of the flux for the $i$th point. Subsequently, as in the case of the original light curve, we analyzed the derived light curve by the epoch folding technique and determined the most probable pulsation period for it. The result of repeating such an analysis $N \approx 1000$ times is a vector of periods $P_i$ for different realizations of the original light curve. The mean of the sample $\langle P \rangle = \sum_i P_i/N$ in this case is the most probable period and standard deviation

$$
\sigma_P = \sqrt{\frac{\sum_i (P_i - \langle P \rangle)^2}{N}}
$$

is the estimate of the error of the period.

**Optical Observations**

The optical observations of 4U 0115+63/V635 Cas carried out by Kriss et al. (1983) allowed its X-ray outburst to be predicted for the first time based on the brightening of the optical star. This additionally confirmed that the object V635 Cas was correctly identified as a normal companion in the system. The model of direct accretion from a stellar wind was rejected based on the measured delay between the optical brightening and the X-ray outburst.

The optical observations of the companion star V635 Cas performed from 1985 to 1990 at the Wise Observatory corroborated the previously reached conclusion that an X-ray outburst is preceded by...
Fig. 1. Overall historical light curve of the X-ray pulsar 4U 0115+63. The source intensity in the 3-100 keV energy band is plotted on the Y-axis in units of the Crab intensity (see text for details). Most significant outbursts are emphasized by the grey color and, together with the evolution of the neutron star spin frequency, are shown in details on top and bottom panels of Fig. 2 respectively. Different symbols mark results of observations by different observatories: open triangles faced down — Vela-5B, open diamonds — Uhuru, filled squares — Ariel-V, filled hexagons — Ginga, crosses — Granat, solid line — BATSE of Compton GRO (see text), open triangles faced left — RXTE/ASM, open circles — INTEGRAL, open squares — Swift/BAT, ‘x’ symbols — MAXI.
Fig. 2. Variations of the flux (upper panels) and pulse frequency (lower panels) of the X-ray pulsar 4U 0115+63 during the most significant outbursts. Symbols on upper panels are the same as for Fig. 1 except for panel g, where results from the RXTE observatory are shown by solid line. Symbols on lower panels are the same as on upper ones with following additions: diamonds denote results of measurements taken from telegrams and other information sources (see text for details); solid line on panel l represents results of the Fermi/GBM measurements. Dashed horizontal lines on lower panels show the last known neutron stars’ spin frequency before the start of the new outburst.
an optical brightening (Mendelson & Mazeh, 1987, 1991). In particular, the 1987 X-ray outburst was preceded by the system’s optical brightening from October 1986 to February 1987. The 1990 outburst was preceded by a large optical brightening that had continued until the completion of the program of observations in March 1990. It should be noted that the object’s optical brightening in 1988 was not accompanied by an X-ray outburst (Mendelson & Mazeh, 1991).

Optical and infrared observations of the source 4U 0115+63 were carried out from 1999 to 2006 (Reig, 2007). Their goal was to test the models of a decretion disk around a Be star proposed previously by Negueruela & Okazaki (2001). A change in the $H_\alpha$ line profile was recorded, suggesting that it is the disk formation and loss that affect the periodicity of type II outbursts in 4U 0115+63 (Negueruela & Okazaki, 2001).

**Orbital Parameters**

As has already been said in the Introduction, the orbital parameters of the pulsar 4U 0115+63 were first calculated from SAS-3 observations (Rappaport et al., 1978). In particular, the orbital period of the system calculated from these data was $24.309 \pm 0.021$ days. Subsequent observations allowed this estimate to be improved. The orbital parameters calculated from BATSE data are used in most papers for correction to the barycenter of the binary system 4U 0115+63 (Bildsten et al., 1997). We used these data here to calculate the pulsation period from INTEGRAL data; the results are presented in the lower panels of Figs 2j-2l and are described in the previous section. On the whole, however, long-term observations of 4U 0115+63 and regular measurements of its orbital parameters suggest that the orbital period in the binary system increases (see Table 2). This is diametrically opposite to the observed changes of the orbital period in ordinary (not Be) high-mass X-ray binaries, where it decreases (Falanga et al., 2013, in preparation).

The source’s high brightness during outbursts and its relatively short pulsation period allowed the change of not only the orbital period in the binary system but also other parameters to be traced. In particular, using UHURU data and results from Rappaport et al. (1978), Kelley et al. (1981) obtained a constraint on the motion of the periastron for the neutron star orbit, $\omega \lesssim 2.11$ yr$^{-1}$. The motion of the periastron for the neutron star orbit determined later from GINGA data during the February 1990 outburst $\dot{\omega} = 0.030 \pm 0.016$ yr$^{-1}$ (Tamura et al., 1992). More recent measurements based on RXTE data give $\dot{\omega} = 0.06 \pm 0.02$ yr$^{-1}$ (Raichur & Paul, 2010).

**SPECTRUM**

**Dependence of the Fundamental Cyclotron Line Energy on Continuum Model**

There exist two main approaches to describing the spectra of the radiation originating in the accretion columns of X-ray pulsars. The first approach consists in a physically proper modeling of the spectrum formation processes and leads to physically justified but often excessively complex models. However, even using a more or less physically proper model does not allow the source’s observed spectrum to be completely described. In particular, Ferrigno et al. (2004) attempted to use the model by Becker & Wolff (2007) in analyzing the spectra of the outburst observed from 4U 0115+63 in March 1999 by the BeppoSAX observatory. However, to completely describe the observed spectra, they had to modify the model and to add a Gaussian component at energy $\sim 9$ keV to it. The latter is required to remove the observed difference between the observational data and the model and, as the authors themselves admitted, carries no any physical meaning. It should be noted that a similar artificial component was also required for the authors to describe the spectra by a phenomenological model. An interesting consequence of adding a Gaussian component to describe the source’s spectrum is the absence of any change in the energy of the fundamental cyclotron line harmonic with the source’s intensity.

The second approach consists in a phenomenological description of the spectrum, i.e., in choosing a sufficiently good model whose rigorous physical justification is ignored. One of two similar models are mainly used for a phenomenological description of the spectra of X-ray pulsars: (1) a power-law spectrum with a cutoff $\sim E^{-\Gamma} \exp \left( -\frac{E}{E_{\text{cut}}} \right)$ and (2) a powerlaw spectrum with a high-energy cutoff (see eq. 1 above).

As has already been said above, several harmonics of the cyclotron absorption line are detected in the spectrum of the X-ray pulsar 4U 0115+63, with the energy of the fundamental harmonic roughly corresponding to $E_{\text{cycl},0} \approx 12B_{12}$ keV, where $B_{12}$ is the magnetic field strength in units of $10^{12}$ G. The width
of these lines is determined by many factors: the spectrum averaging over the pulse profile, the high temperature of the scattering region, the natural quantum broadening, the dispersion of the magnetic field strength over the scattering region, etc.

There exist several models that describe the shape of the cyclotron absorption lines. Here, we used the multiplicative cyclabs model from the XSPEC package

\[ M(E) = \exp \left[ -\tau \left( \frac{(W_f E/E_{\text{cycl}})^2}{(E - E_{\text{cycl}})^2 + W_f^2} \right) \right] \tag{2} \]

, where \( \tau \) is the depth of the cyclotron absorption line, \( E_{\text{cycl}} \) (in keV) is the energy of the cyclotron line center, and \( W_f \) (in keV) is the cyclotron line width. In general, the positions of the cyclotron absorption features in the pulsar spectrum depend on the apparent geometry, i.e., on the pulse phase, because the scattering cross section depends on the angle between the photon direction and the direction of the magnetic field vector. However, here we disregarded this effect for a simple analysis and studied the pulsar spectra averaged over the pulse profile.

The X-ray pulsar 4U 0115+63 has the longest history of searching for and detecting cyclotron absorption lines (for the discovery and interpretation of the fundamental and first harmonics, see above). Based on RXTE data, Heindl et al. (1999) detected a second harmonic at energy \( \approx 33.56 \) keV at the descending part of the smaller peak in the pulse profile, which provides evidence for different formation regions of these lines. A third harmonic in this source’s spectrum was detected by Santangelo et al. (1999) at energy 49.5 keV based on BeppoSAX data and by Tsygankov et al. (2007) at energy 44.93 keV based on INTEGRAL data. The detection of a fourth harmonic in the source’s spectrum was reported by Ferrigno et al. (2003) based on BeppoSAX data and by Müller et al. (2013) based on RXTE data. However, the harmonic energies reported by the authors differ significantly, \( \approx 53 \) and \( \approx 60 \) keV, respectively.

A change of the cyclotron line energy with luminosity has been found for the first time for the pulsar 4U 0115+63 among all X-ray Be transients. In particular, Mihara et al. (2004) did not detect the two expected cyclotron lines at \( \sim 11 \) and \( \sim 22 \) keV in the descending part of the weak \( (L_x = 2 \times 10^{37} \text{ erg s}^{-1}) \) outburst in March 1991 in the LAT/GINGA spectra. Instead of this pair, they detected one strong absorption line at energy \( \sim 16 \) keV. Further studies based on RXTE data (Nakajima et al. 2006) showed the energy of the fundamental cyclotron line harmonic to change from \( \sim 11 \) to \( \sim 16 \) keV at the source’s luminosity \( L_x < 4 \times 5 \times 10^{37} \text{ erg s}^{-1} \). Such a behavior was subsequently confirmed by Tsygankov et al. (2007). Apart from the variability of the cyclotron absorption line energy on long time scales, the pulsar 4U 0115+63 also exhibits variability of the cyclotron line energy from pulse to pulse (Klochkov et al. 2011), which confirms the anticorrelation between its energy and luminosity.

Despite the enormous number of observations and studies of cyclotron lines in the spectrum of the X-ray pulsar 4U 0115+63 (see above), several questions still remain open. One of the main questions is whether the observed changes in the positions of the fundamental cyclotron line with luminosity are real (Nakajima et al. 2006; Tsygankov et al. 2007; Klochkov et al. 2011) or they are related to the chosen continuum model (Ferrigno et al. 2003; Müller et al. 2013). Following the approach proposed by Ferrigno et al. (2003), the authors of the latter paper added an artificial Gaussian component at energy \( \sim 10 \) keV to the phenomenological continuum model. In this case, the anticorrelation between the cyclotron line position and luminosity observed previously in the RXTE and INTEGRAL data during the March/April 2008 outburst disappeared.

To test the conclusions reached by Müller et al. (2013), we investigated the spectra of the X-ray pulsar 4U 0115+63 and the dependence of the cyclotron absorption line characteristics on the source’s luminosity using all of the available data obtained by the RXTE/PCA spectrometer during intense outbursts since 1995. Using the XSPEC version v12.7.1b package, we fitted the phase-averaged spectra in the 4-28 keV energy band with two different models. The first model is a power law with a high-energy cutoff multiplied by two cyclotron lines plus an iron line in the form of a Gaussian. We chose this model as giving the best \( \chi^2 \) values among all continuum models. The energy and width of the fluorescent iron line were fixed at the following values: \( E = 6.4 \) keV and \( \sigma = 0.2 \) keV; the iron line intensity was a free parameter.

When using this model, the anticorrelation between the cyclotron line energy and luminosity that has already been found by Mihara et al. (2004); Nakajima et al. (2008); Tsygankov et al. (2007) manifests itself in all outbursts. Obviously, the cyclotron line energy lies within the range 11-12
Fig. 3. Energy of the fundamental and first harmonics of the cyclotron absorption line detected in the spectrum of the pulsar 4U 0115+63 versus its luminosity for different continuum models. The data were obtained from the results of PCA/RXTE observations during bright outbursts (indicated by different symbols). The CSRF energies when the spectra were fitted by a power law with a high-energy cutoff are presented in the left panels. An anticorrelation between the position of the fundamental harmonic and luminosity (lower panel), which does not manifest itself for the first harmonic (upper panel), can be seen. The energies of the cyclotron line harmonics when the spectra were fitted by a power law with a high-energy cutoff with the addition of an emission line with a Gaussian profile at an energy of about 10 keV are presented in the right panels. The absence of an anticorrelation between the cyclotron line energies and pulsar luminosity is obvious.
keV at high luminosities and rises up to 16 keV with decreasing luminosity when the source’s luminosity passes through $L_x \sim (4 - 5) \times 10^{37}\text{erg s}^{-1}$ (see Fig. 3, the lower left panel). The photon index $\Gamma$ for all fits lies within the range $-0.1-0.5$ and shows no correlation with the line energy. It is important to note that whereas the energy of the fundamental harmonic changes significantly, the energy of the first harmonic remains essentially constant (Fig. 3, the upper left panel). Thus, it can be concluded that either we chose not quite a proper continuum model or the first and fundamental harmonics are formed in distinctly different regions.

No anticorrelation between the luminosity and position of the fundamental cyclotron absorption line harmonic is observed when using another continuum model proposed by Ferrigno et al. (2009). This model is the sum of a power law with a high-energy cutoff and a broad emission feature with a Gaussian profile energy $\approx 10$ keV and width $\approx 3$ keV. As in the previous case, two cyclotron lines and an iron line are added to this model.

The results of applying this model are presented in Fig. 3 (right panels). It can be seen that when using this model, the energy of the fundamental cyclotron absorption line harmonic does not change practically with the source’s luminosity, and the relationship between the energies of the fundamental and first harmonics remains constant. This stems from the fact that the motion of the emission line with a Gaussian profile and the change in its intensity “mask” the change in the cyclotron absorption line energy. This assertion was tested through the generation of spectra in the XSPEC package using the fakeit command and the (powerlaw * highcutoff + gauss) * cyclabs * cyclabs model followed by their fitting with the powerlaw * highcutoff * cyclabs * cyclabs model. In this case, the behavior of the energy of the fundamental cyclotron absorption line harmonic in the generated spectra closely followed its behavior when the observed spectra were fitted directly.

As has already been noted above, the Gaussian emission line at energy $\sim 10$ keV being added to the continuum spectrum has no any physical meaning. Its inclusion in the model formally improves the quality of the fit to individual spectra with confidence levels $\approx 2 - 3\sigma$. Another factor that makes it difficult to model the spectrum of 4U 0115+63 is that the cutoff energy $E_{\text{cut}}$ is very close to the energy of the fundamental cyclotron absorption line harmonic and it turns out to be very problematic to properly take into account the influence of different factors.

Thus, the above results provide evidence for a model strong dependence of the measured positions and evolution of the cyclotron lines in the spectrum of the X-ray pulsar 4U 0115+63. A physically justified model of the spectra for X-ray pulsars is needed to properly describe its spectrum and to answer the question about the evolution of the cyclotron absorption line energy.

**Broadband Spectrum from INTEGRAL Data during the 2011 Outburst**

Figure 4 shows the spectrum of 4U 0115+63 in a wide energy range, 4-100 keV, obtained from IBIS/ISGRI and JEM-X (INTEGRAL) data during the 2011 outburst. During this outburst, the source was observed by the INTEGRAL observatory several times in states with different luminosities (from $L_x \approx 7 \times 10^{37}$ erg s$^{-1}$ to $L_x \approx 10^{37}$ erg s$^{-1}$). For the presentation in Fig. 4, we used the data obtained in revolutions 1061 and 1063 near the outburst peak ($L_x \approx 7 \times 10^{37}$ erg s$^{-1}$).

The data obtained were fitted by the models, from a simple power law with a highenergy cutoff up to the model with five harmonics of the cyclotron absorption line. To align the ISGRI and JEM-X spectra, we used a multiplicative factor whose value reflects different calibrations of different instruments but, nevertheless, turns out to be close to unity. The spectral continuum parameters obtained through our fitting for the bright state agree well with those measured for the source being studied by other observatories: photon index $\approx 0.2$, $E_{\text{cut}} \approx 8.7$ keV, and $E_{\text{fold}} \approx 11.6$ keV.
The fundamental and two first harmonics of the cyclotron absorption line at energies $\approx 11, 24$, and 35.6 keV, respectively, are also detected in the source’s spectrum at a high confidence level ($> 5\sigma$). Adding higher harmonics also improves the quality of the fit, but the confidence level of their detection turns out to be not so high — the confidence levels of the third and fourth harmonics at energies 48.8 and 60.7 keV are $\sim 2\sigma$ and $\sim 2.5\sigma$, respectively. It is important to note that the measured energy of the fourth harmonic agrees well with the measurements made by Müller et al. (2013) based on RXTE data and differs significantly from the energy measured for it from BeppoSAX data (Ferrigno et al. 2009). The component related to the fluorescent iron line at energy 6.4 keV was also included in the model. However, because of the well-known problems with the JEM-X response matrix at energies close to its position, it is very difficult to make any conclusions about its intensity and presence in the source’s spectrum.

In conclusion, note that adding a Gaussian line at energy $\sim$10 keV to the model does not lead to significant improvements in the quality of the fit to the spectra obtained from INTEGRAL data. This may be because the quality of the JEM-X data in the 3-30 keV energy band is lower than that of the PCA/RXTE data used in the previous section and because the exposure time of each observations is relatively short ($\sim$50 ks). Without this component, the behavior of the energy of the fundamental cyclotron absorption line harmonic almost exactly follows Fig. 3 (lower left panel) — at the source’s high luminosity, the line is in the range 11.5-12 keV; as the luminosity decreases, it is shifted to 15.5-16 keV.

CONCLUSIONS

A review of the available data on the X-ray pulsar 4U 0115+63, a member of the binary system with the Be star V635 Cas, was carried out. The history of X-ray outbursts from the source recorded over a more than forty-year-long history of its observations based on data from more than ten observatories and instruments was presented. The evolution of the neutron star spin frequency over the entire history of its observations, including the results of recent measurements made by the INTEGRAL observatory during the 2004, 2008, and 2011 outbursts, was analyzed.

Based on the INTEGRAL data obtained at our request during the 2011 outburst, we constructed broadband spectra of the pulsar for various luminosity levels. Five harmonics of the cyclotron absorption line at energies $\approx 11, 24, 35.6, 48.8, \text{ and } 60.7$ keV were shown to be detected in the source’s spectrum, with the energy of the fundamental harmonic changing from 11-12 keV in its bright state to 15.5-16 keV as its luminosity decreases.

To investigate the reality of the anticorrelation between the fundamental harmonic energy and the source’s luminosity as well as its dependence on the spectral continuum shape, we analyzed the spectra based on all the available PCA/RXTE data obtained during bright outbursts detected from the pulsar 4U 0115+63 in 1995 – 2011. We showed that including this additional component in the form of a Gaussian broad emission line at energy $\sim$10 keV suggested previously by Ferrigno et al. (2009) and Müller et al. (2013) in the model led to the disappearance of the $E_{\text{cyc,0}} - L_x$ anticorrelation. Our modeling showed that this effect results from the change in emission line parameters that “masks” the possible anticorrelation. It is necessary to note that it is rather problematic to physically justify the presence of an additional emission component in the spectrum. Another important factor that makes it difficult to model the spectrum of 4U 0115+63 is that the cutoff energy $E_{\text{cut}}$ is very close both to the energy of the fundamental cyclotron absorption line harmonic $E_{\text{cyc,0}} \approx 11$ keV and to the energy of the artificially added emission line at $\approx$10 keV. Collectively, all of these factors do not allow the question about the presence or absence of an $E_{\text{cyc,0}} - L_x$ anticorrelation for the X-ray pulsar 4U 0115+63 to be unambiguously answered at present. This requires a physically justified model of the spectra for X-ray pulsars.

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