PULSE PROFILES AND CYCLOTRON LINE ENERGY DEPENDENCE ON X-RAY PULSARS LUMINOSITY

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ABSTRACT

We present the results of broad band (3-100 keV) observations of several X-ray pulsars with the INTEGRAL and RXTE observatories. We concentrate on the luminosity and energy dependence of the pulse profile and the variations of the cyclotron line energy. In V0332+53 the line energy changes nearly linearly with the source luminosity, while in 4U0115+63 its behavior is more complicated. Strong variations of the pulse profile with energy and source intensity were found for both pulsars; in V0332+53 the changes of the pulse profile near the cyclotron line are especially drastic. The preliminary results obtained for Her X-1 and GX 301-2 in a high intensity state show the absence of significant pulse profile changes with energy. Results and possible emission mechanisms are briefly discussed in terms of theoretical models of accreting pulsars.

Key words: X-ray pulsars; binaries.

1. INTRODUCTION

In this work two transient X-ray pulsars, V0332+53 and 4U0115+63, and two persistent ones, Her X-1 and GX 301-2, were studied. The first two sources are members of high-mass X-ray binary systems with Be class stars and demonstrate regular powerful outbursts in which their luminosities can reach $several \times 10^{38}$ erg s^{-1}. The distinctive peculiarity of both sources is that not only the main harmonics of the cyclotron resonance scattering feature (CRSF) are registered in their X-ray spectra but also their higher harmonics. The another two X-ray pulsars belong to different classes: GX 301-2 is a system with a supergiant companion, Her X-1 is a low-mass X-ray binary system. Spectra of both sources also include CRSFs (see, e.g., [1]).

2. CYCLOTRON LINE ENERGY

2.1. V0332+53

The pulsar V0332+53 was observed during a powerful outburst in 2004-2005 with the range of measured luminosities from $\sim 10^{37}$ to $\sim 5 \times 10^{38}$ erg s^{-1}. The significant number of V0332+53 observations carried out with the INTEGRAL and RXTE observatories allowed us to reconstruct the source spectrum at different phases of the outburst and to trace the evolution of its parameters in detail ([2]).

As a whole, the pulsar spectrum during the outburst can be well described by a power law with an exponential cutoff at high energies modified by several harmonics of CRSF (see, e.g., [3]; [4]) that is observed for several X-ray pulsars. But the behaviour of the cyclotron line in this source deserves special attention, as its position is not constant. The line energy dependence on the source luminosity obtained from *INTEGRAL* and *RXTE* data is shown in Fig. 1 by dark triangles and squares, respectively. The formal fitting of this dependence with a linear relation gives $E_{cycl,1} \simeq -0.10L_{37} + 28.97$ keV, where L_{37} – the source luminosity in units of 10^{37} erg s^{-1}. Assuming that for low luminosities the emission comes practically from the neutron star surface (see below) we can estimate the magnetic field on the surface

$$B_{NS} = \frac{1}{\sqrt{1 - \frac{2GM_{NS}}{R_{NS}c^2}}} \frac{28.97}{11.6} \simeq 3.0 \times 10^{12} \text{G} \qquad (1)$$

where R_{NS} and M_{NS} are the neutron star radius and mass, respectively.

It was shown in [5] that there is a critical value of the luminosity ($L^* \sim 10^{37}$ erg s^{-1}) dividing two accretion regimes: the regime when the influence of the radiation on the falling matter is negligible and the regime when this influence is significant. When $L < L^*$, the matter free-fall zone is extended almost down to the surface of the neutron star. In the opposite case ($L > L^*$), observed for V0332+53, the radiation-dominated shock rises high above the neutron star surface. Almost all of the kinetic energy of the infalling gas is lost in this shock, and is then emitted laterally by the sides of the accretion column.
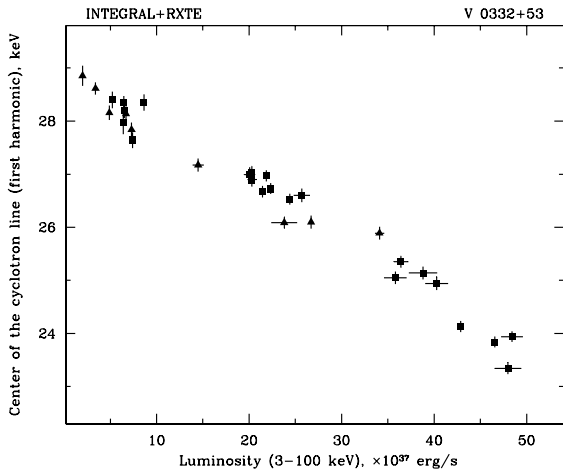
Figure 1. The cyclotron line energy dependence on the source luminosity (3-100 keV) for V0332+52. Triangles are INTEGRAL results, squares are RXTE ones.
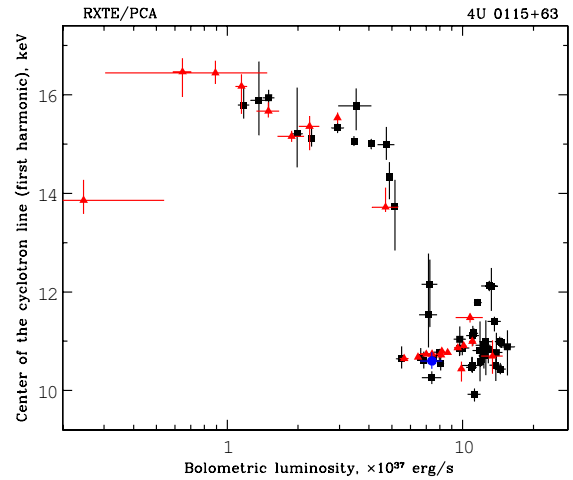

Figure 2. The cyclotron line energy dependence on the 4U0115+63 luminosity obtained by RXTE during outbursts of 1999 (solid squares) and 2004 (solid triangle) and by INTEGRAL during 2004 yr (solid circle).

In [5] and [6] is showen that the height of the shock H changes practically linearly with changes of the accretion rate, $H \propto \dot{m}$, in a wide range of values $\dot{m}$, i.e. the shock height grows linearly when the source luminosity increases and can reach several kilometers for high luminosities.

In the case of V0332+53 the maximum relative change of the line energy and, consequently, the corresponding magnetic field is about $\sim 25\%$. In an approximation of a dipole field of the neutron star, it corresponds to a 7.5% relative change of the height h where the feature is formed. At the end of the outburst, the source luminosity falls to $\sim 10^{37}$ erg s^{-1}, the column height decreases and we detect the emission coming virtually from the neutron star surface. Taking the neutron star radius $R_{NS} \sim 10^6$ cm we can estimate the maximum height $h \sim 750$ m, that is much less than the shock height H expected for such luminosities.

Due to the fact that only a small fraction of the energy accumulated in the accreting matter is emitted at the shock ([5]) and its main part goes into the extended sinking zone below the shock the registered emission is a superposition of emissions from different heights above the neutron star surface. Therefore, we can consider the height h as averaged or "effective" height of the formation of the cyclotron feature not coinciding with the position of the shock itself.

2.2. 4U0115+63

The spectrum of 4U0115+63 also can be well fitted by the power-law model with an exponential cutoff at high energies and it also contain CRSF with higher harmonics. The energy of this feature depends on the source luminosity, but the picture of these changes is not as clear as in case of V0332+53. The cyclotron line energy depen-

dence on the source luminosity obtained during outbursts of 4U0115+63 in 1999 and 2004 with RXTE and INTEGRAL observatories (see also [7] and [8] and references therein) is presented in Fig. 2. The observed dependence can be roughly divided in two parts with different values of the cyclotron line energy, ~ 11 and ~ 14 keV. A drastic transition between these energies is observed near the source luminosity $\sim 5 \times 10^{37}$ ergs s^{-1} in both outbursts. With further decreasing of the source luminosity the CRSF energy is smoothly increasing and reaches a value of about 16 keV to the outburst end. Assuming that for the low-luminosity state the cyclotron feature is formed near the neutron star surface, we can estimate the magnetic field of the neutron star using equation (1), as $B_{NS} \simeq 1.5 \times 10^{12}$G.

3. PULSE PROFILE

The observed strong spectral and geometrical changes of accretion column might lead to significant changes in other observable characteristics of pulsars, for example, in the shape of the pulse profile.

3.1. V0332+53

Two three-dimensional pulse profiles (distributions of pulse intensities along the pulse phase and energy relative to the mean value) for different states of V0332+53, $\sim 3.4 \times 10^{38}$ (left part) and $\sim 7.3 \times 10^{37}$ erg s^{-1} (right part), are shown in Fig. 3 (upper panel). The light and dark stripes represents regions of lower and upper wings of cyclotron lines. In the bottom panels of Fig. 3 two-dimensional distributions of pulse profile intensities are demonstrated by different colors and levels of equal in-
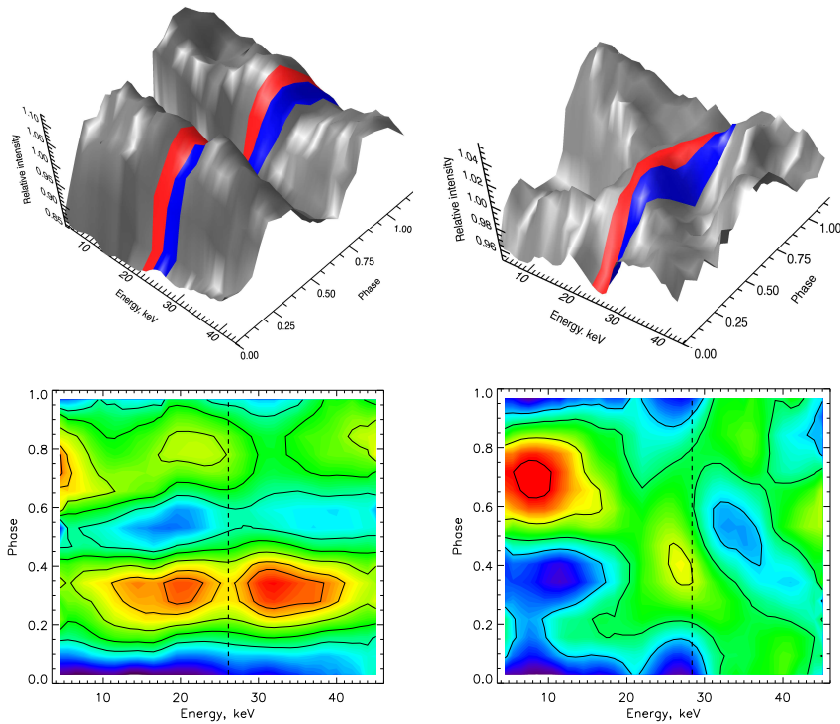
Figure 3. 3D evolution of the pulse profiles (top) and 2D-distributions of profile intensities (bottom) for different luminosities. Positions of the cyclotron line center are shown by dashed lines. Left part of the figure corresponds to the mean luminosities $\sim 3.4 \times 10^{38}$ erg s^{-1} and right one $- \sim 7.3 \times 10^{37}$ erg s^{-1}.

tensities. It is interesting to trace changes of the maximum intensities for both observations: in the high state the positions of both peaks are practically unchanged with energy, although their relative intensity is changed; in the low state the profile became single-peaked at energies just below the cyclotron line with a drastic transition to the double-peaked just above the line energy (Fig. 3).

The exact explanation of the pulse profile is complicated, many geometrical and physical processes can affect the pulse profile changes. For example, the gas accretion stream flowing along the Alfven surface covers only part of this surface. Spinning with the same angular velocity as the neutron star it can periodically shade from the observer different parts of emission regions, that can explain the different intensities of peaks in the pulse profile and their changes with energy ([9]).

The observed changes of the source pulse profile near the cyclotron frequency is difficult to describe in detail within the framework of current models. Naturally, they can be connected with peculiarities of the radiation beaming near the cyclotron frequency ([10]; [11]). In particular, as e.g. [12] showed, the cyclotron line shape demonstrates a strong angular dependence. The plasma is more transparent at large angles than at small ones for energies below and above the line energy. Therefore photons will escape predominantly in the directions of large angles, i.e. the radiation beaming in different energy channels near the

cyclotron line will be strongly different. But the exact physical picture is unclear yet.

3.2. 4U0115+63

Two-dimensional distributions of pulse profile intensities for 4U0115+63 obtained with the RXTE observatory are shown in Fig. 4. In the bright state the profile is double-peaked up to $\sim 10 - 20$ keV (pulses at phases ~ 0.3 and ~ 0.7); with the decrease of the source luminosity the relative intensity of a second peak is decreasing and the profile becomes single-peaked. The observed pulse profile dependenes on energy and luminosity can be roughly understood in terms of a simple geometrical model: the angle between the rotation axis and direction to the observer has such a value that allows us to see one accretion column entirely, but another column is partially obscured by the neutron star surface. Thus, the hottest parts of the second column are obscured and the corresponding peak in the profile should disappear with energy increasing. In terms of this model the decrease of the second peak with decreasing luminosity can be explained by the reduction of the accretion column height and consequently by the obscuration of its colder parts. Naturally, for an accurate description of the pulse-profile behaviour more complicated models are needed. For example it is important to know the beam function of the accretion column at different luminosities and energies. Due to the closeness
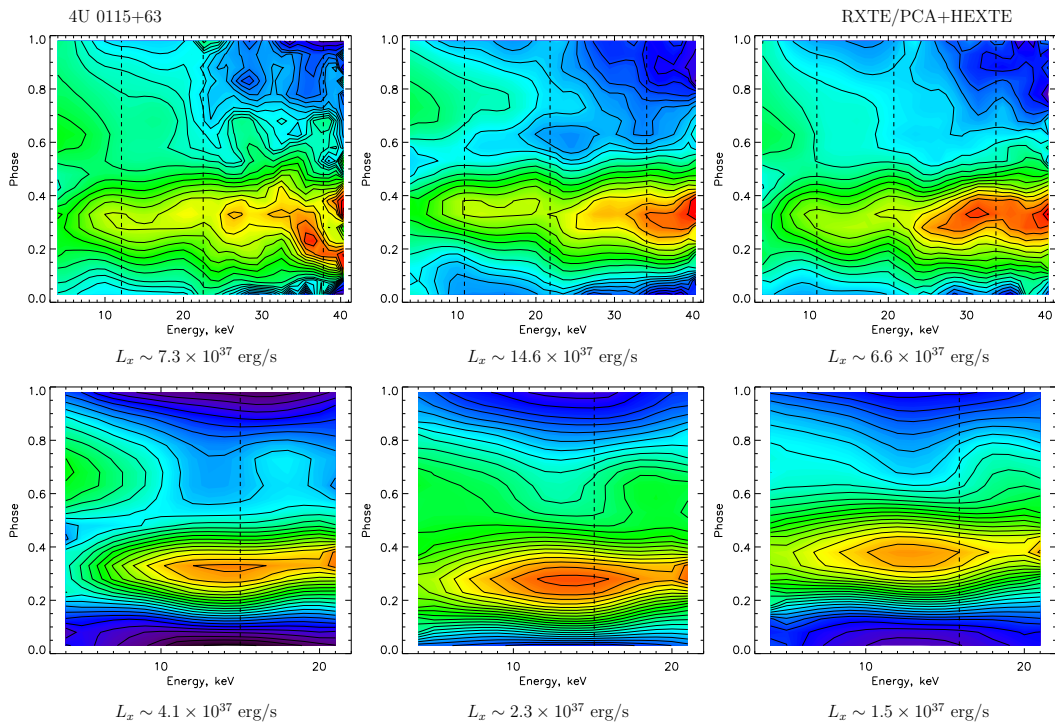
4U 0115+63   RXTE/PCA+HEXTE

$L_x \sim 7.3 \times 10^{37}$ erg/s $L_x \sim 14.6 \times 10^{37}$ erg/s $L_x \sim 6.6 \times 10^{37}$ erg/s

$L_x \sim 4.1 \times 10^{37}$ erg/s $L_x \sim 2.3 \times 10^{37}$ erg/s $L_x \sim 1.5 \times 10^{37}$ erg/s

Figure 4. 2D-distributions of profile intensities for different source 4U0115+63 luminosities (3-100 keV). Positions of the cyclotron line center are shown by dashed lines. At the three last maps (for low luminosity cases) only PCA data is shown.
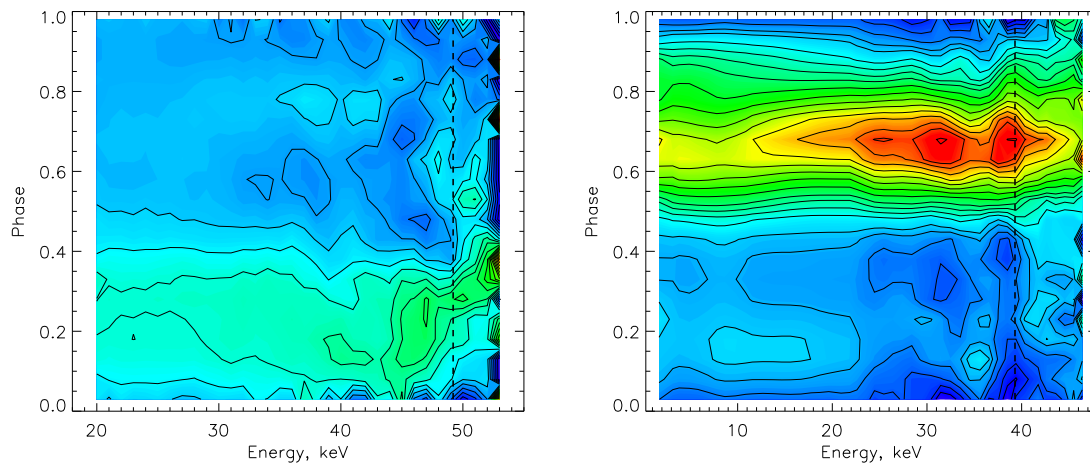

Figure 5. 2D-distributions of profile intensities for GX 301-2 (left panel) and Her X-1 (right panel) at high intensity state. Positions of the cyclotron line center are shown by dashed lines.

of radiating areas to the neutron star surface some relativistic effects (e.g., light bending) should be taken into account also. Thus, the construction of even a simple model is very complicated. Nevertheless, if the above assumptions are correct they can give us the possibility to estimate some basic geometrical parameters of this X-ray pulsar.

We did not detect such drastic changes in pulse profile near the cyclotron frequency as in the case of V0332+53, but the preliminary analysis shows that the profile demonstrates a wavy behaviour with energy: near the main cyclotron frequency and its harmonics the phase of the first peak in the profile is slightly shifting "down"; between CRSF harmonics the phase is shifting "up" (Fig. 4).

3.3. GX 301-2 and Her X-1

Two another well known X-ray pulsars with cyclotron features in their spectra, Her X-1 and GX 301-2, were studied to search for pulse-profile changes with energy. The intensity maps of pulse profiles of these pulsars in high-intensity states are presented in Fig. 5. In the left panel is shown the pulse profile of GX 301-2 obtained with the IBIS telescope onboard the INTEGRAL observatory in the hard energy band (18-60 keV). The Her X-1 pulse profile obtained with the RXTE observatory in the 3-40 keV energy band is shown in the right panel. The preliminary analysis shows that as in the case of 4U0115+63 no drastic changes of the pulse profile with energy and near the cyclotron frequency are observed.

4. CONCLUSION

We presented results of the analysis of the *INTEGRAL* and *RXTE* data obtained for two transient sources, V0332+53 and 4U0115+63, during outbursts, and two persistent ones, GX 301-2 and Her X-1. The most important and interesting results are:

– for the first time we studied in detail the evolution of the cyclotron line energy in the spectrum of V0332+53 with source luminosity and showed that it is linearly increasing with decreasing luminosity in the same way as the change of the height of the accretion column;

– strong pulse profile changes with luminosity, especially near the cyclotron line, are revealed for V0332+53;

– it was shown that for 4U0115+63 the cyclotron line energy depends on the source luminosity in a complex manner;

– a possibly wavy behaviour of the 4U0115+63 pulse profile with energy is revealed;

– preliminary results on GX 301-2 and Her X-1 do not reveale evident changes of their pulse profiles with energy.

Detailed studies of the population of pulsars with CRSFs are in a progress.

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