УДК 524.354.4

ИССЛЕДОВАНИЕ ЗАВИСИМОСТИ ФОРМЫ ПРОФИЛЯ ИМПУЛЬСА И ЦИКЛОТРОННОЙ ЧАСТОТЫ ОТ СВЕТИМОСТИ ПУЛЬСАРОВ

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

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В работе представлены результаты наблюдений рентгеновских пульсаров обсерваториями ИНТЕГРАЛ и RXTE в широком диапазоне энергий. Основное внимание уделялось исследованию зависимости формы профиля импульса от светимости пульсара и энергетического диапазона, а также изменению положения циклотронной линии в спектре источников. Показано, что для пульсара V0332+53 последняя величина меняется практически линейно со светимостью, тогда как для источника 4U0115+63 зависимость более сложная. Для обоих пульсаров обнаружена сильная зависимость формы профиля импульса от собственной светимости пульсаров и энергетического диапазона.

We present the results of broad band (3–100 keV) observations of 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 varies nearly linearly with the source luminosity, while in 4U0115+63 its behavior is more complicated. Strong variations of the pulse profile with the energy and source intensity were found for both of pulsars; in V0332+53 the changes of the pulse profile near the cyclotron line are especially drastic. Results and possible emission mechanisms are briefly discussed in terms of theoretical models of accreting pulsars.

Cyclotron line energy

V0332+53

The pulsar V0332+53 was studied during the powerful outburst in 2004–2005 with the range of measured luminosities from 10^{37} to 5×10^{38} erg/s. 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 ([7]).

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 ([3], [6]) that is observed for several X-ray pulsars. But the behaviour of the cyclotron line in this source deserves a special attention, as its position is not a constant; its energy dependence on the source luminosity obtained from INTEGRAL and RXTE data is shown in Fig. 1. The formal fitting of this dependence with a linear relation gives $E_{cycl,1} \cong -0.10L_{37}+28.97$ keV, where L_{37} - the source luminosity in units of 10^{37} erg/s. Believing that for low luminosities the emission come practically from the neutron star surface (see below) we can estimate the magnetic field on the surface

$$B_{NS}=1/(1-2GM_{NS}/R_{NS}c^2)^{1/2}(28.97/11.6)=3\times10^{12}\text{ G},$$

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

There is a critical value of the luminosity (L^*~10^{37} erg/s) dividing two accretion regimes ([1]): 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.

[1] and [4] showed that the height of the shock H changes practically linearly with changing of the accretion rate, $H\sim \dot{m}$, in a wide range of values $\dot{m}$, i.e. the shock height grows linearly when the source luminosity is increased and can reach several kilometres for high luminosities.

In case of V0332+53 the maximum relative change of the line energy and, consequently, the corresponding magnetic field is about ~25 %. In an approaching of the dipole field of the neutron star, it corresponds to a 7.5 % relative change of the height h where the feature is formed. Taking the neutron star radius R_{NS}~10^6 cm we can estimate the maximum height h~750 m, that is much less than the shock height H expected for such luminosities.

Main part of the energy accumulated in the accreting matter goes into the extended sinking zone below the shock ([1]), therefore the registered emission is a superposition of emissions from different heights above the neutron star surface and the height h can be considered as some averaged or “effective” height of the formation of the cyclotron feature.

4U0115+63

The spectrum of 4U0115+63 also can be well fitted by a power law 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 much more complicated (Fig. 2) then in case of V0332+53. The cyclotron line energy and source luminosity time dependences can be divided in two parts: where these dependences can be approximated by Gaussians (high luminosity state) and where they become nearly linear (below ~6×10^{37} erg/s). It was obtained that in the high luminosity state a shift between these two Gaussians is about δt~6 days (see Fig. 2). The physical reasons of such a behaviour are still unclear and the work is in progress ([8]). If we suppose that for the low luminosity state the cyclotron feature is formed near the neutron star surface than we can estimate the magnetic field of the neutron star as B_{NS}~1.5×10^{12} G.

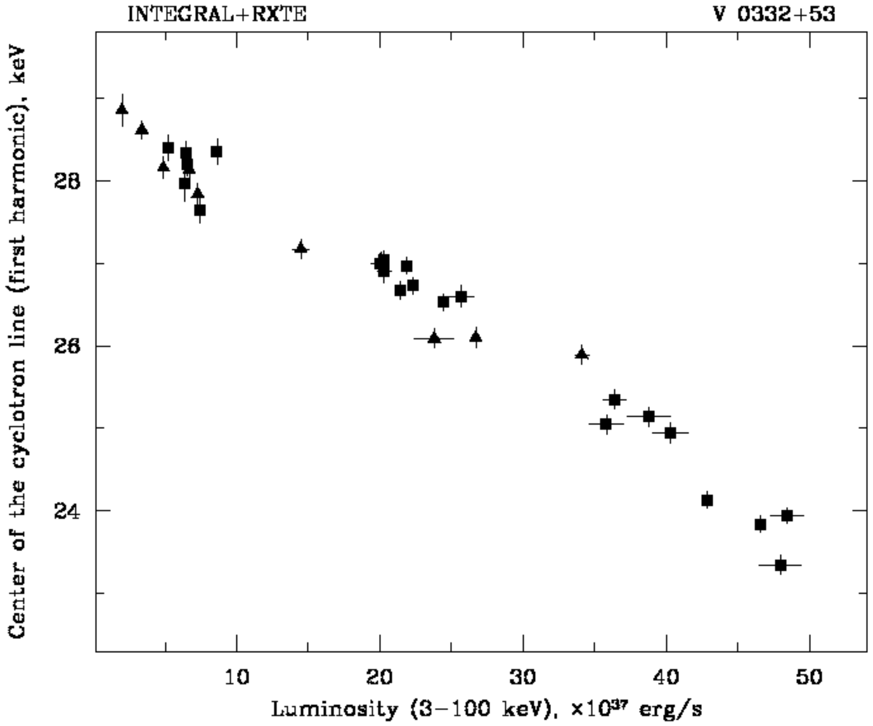

Figure 1. The cyclotron line energy dependence on the source luminosity (3–100 keV) for V0332+52. Triangles are INTEGRAL results, squares are RXTE ones.

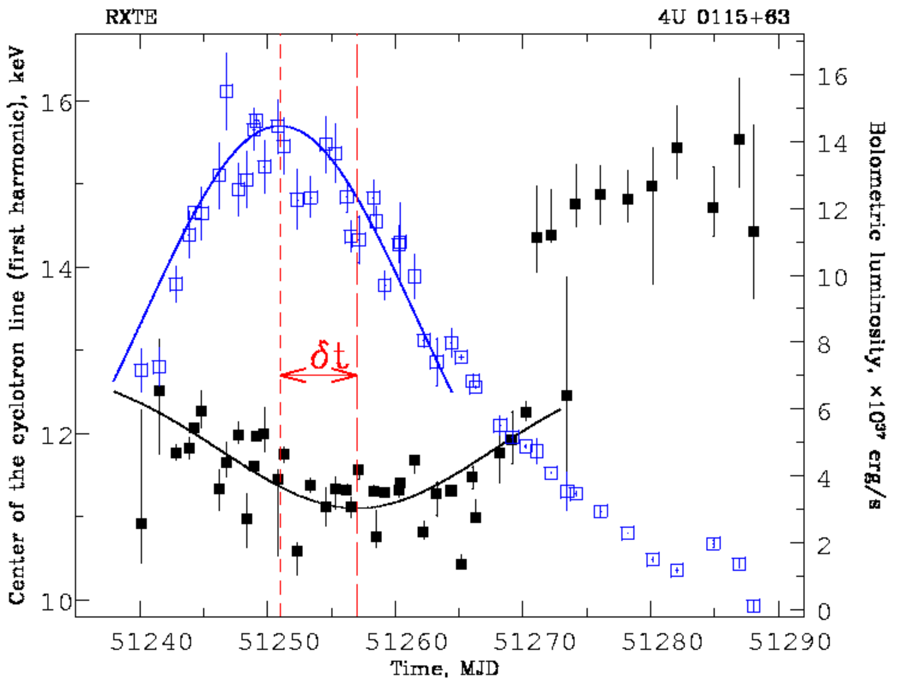

Figure 2. The cyclotron line energy (solid squares) and source luminosity (open squares) time dependence obtained during the outburst of 4U0115+63. Solid lines represents best fit Gaussians.

Pulse profile

The observed strong spectral and geometrical changes should lead to significant changes in other observable exhibitions of pulsars, for example, in the shape of the pulse profile.

V0332+53

The observed peculiarities in the pulse profile behavior can be divided in two main groups: an asymmetrical evolution of the double-peaked profile in a wide energy band and its drastic changes near the main harmonics of the cyclotron line in the low luminosity state. Two three-dimensional pulse profiles (distributions of relative pulse intensities along the pulse phase and energy) for different states of V0332+53, ~3.4×10^{38} (left part) and ~7.3×10^{37} erg/s (right part), are shown in Fig. 3 (upper panel). The red and blue stripes represents regions of lower and upper wings of cyclotron lines. In bottom panels of Fig. 3 two-dimensional distributions of pulse profile intensities are demonstrated by different colors and levels of equal intensities. It is interesting to trace changes of the maximum intensities for both observations: in the high state the positions of both peaks

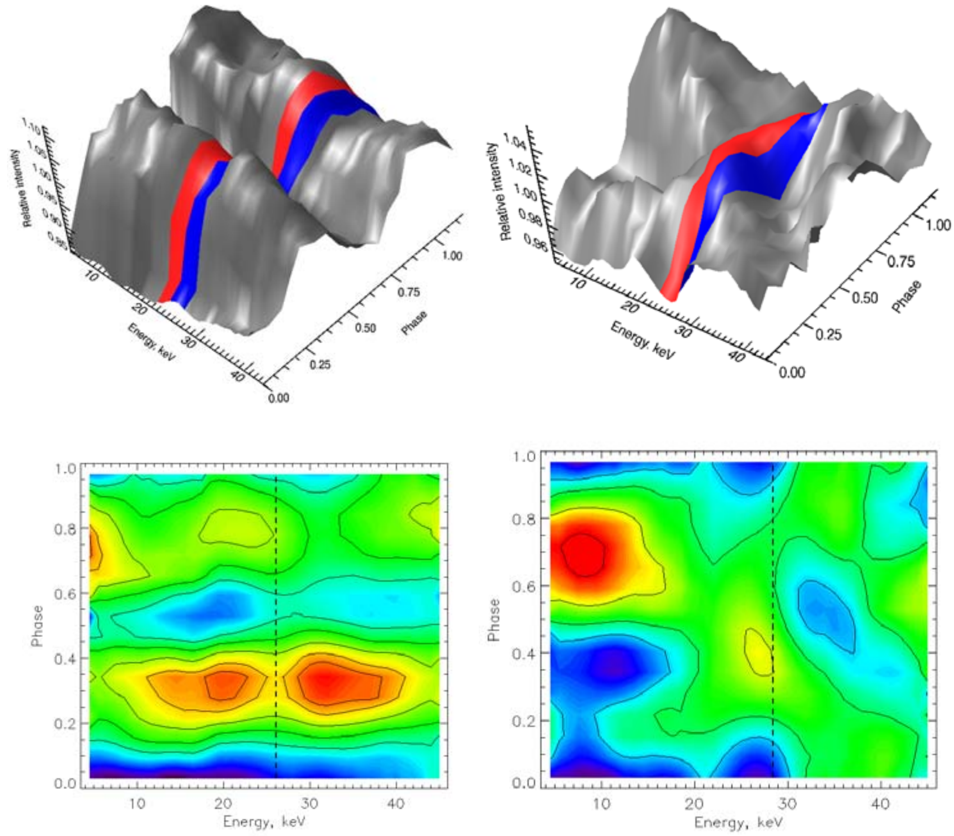

Figure 3. 3D evolution of the pulse profiles (top) and 2D-distributions of profile intensities (bottom) for different luminosities. Positions of the cyclotron line center are shown by dashed lines.

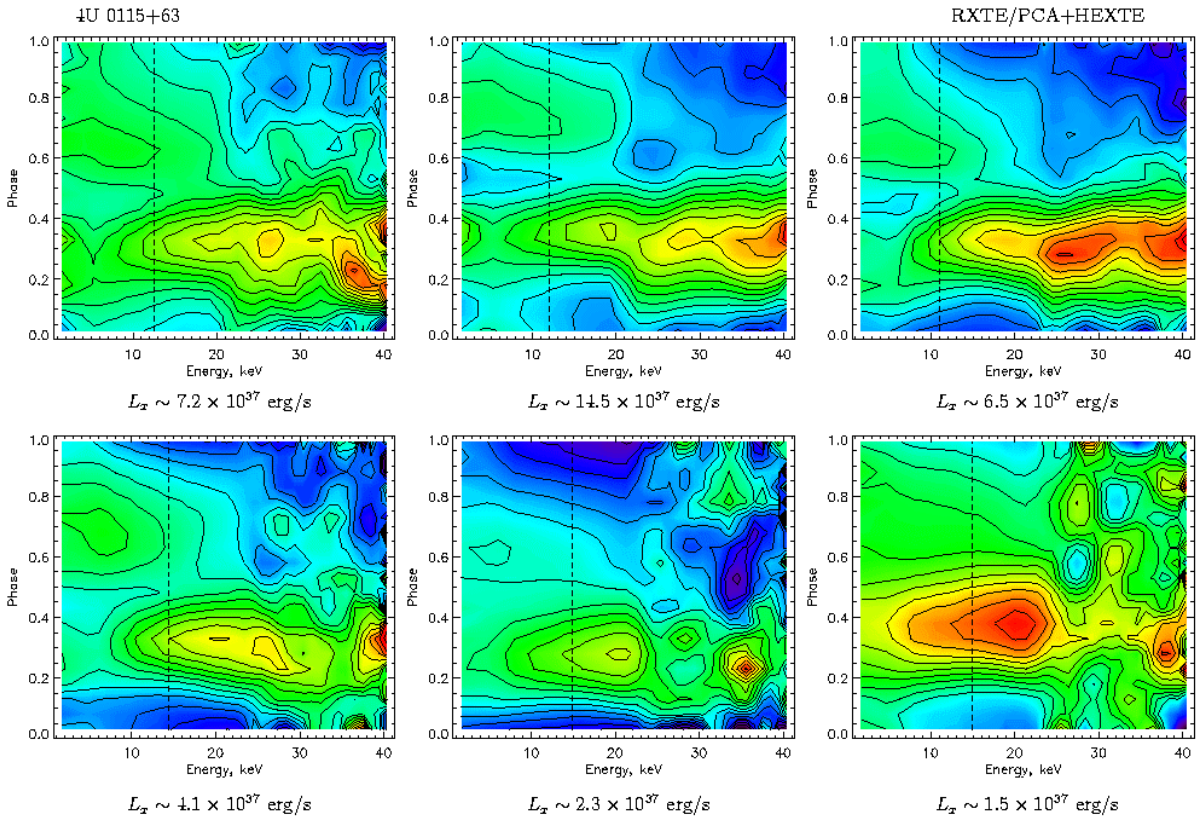

Figure 4. 2D-distributions of profile intensities for different source 4U0115+63 luminosities (3-100 keV). Positions of the cyclotron line center are shown by dashed lines.

are practically unchanged with the energy; 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.

Partially, changes of the source pulse profile near the cyclotron frequency can be connected with peculiarities of the radiation beaming near the cyclotron frequency ([2]). As e.g. [4] 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.

4U0115+63

Two-dimensional distributions of pulse profile intensities of 4U0115+63 are shown in Fig. 4. In the bright state the profile is double-peaked up to ~20 keV; with the decreasing of the source luminosity the relative intensity of a second peak is decreasing and the profile become single-peaked. For the rough explanation of the observed pulse profile dependences on the energy and luminosity a simple geometrical model can be proposed: the angle between the rotation axis and direction to the observer has a such value that allow 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 the growing of the energy. In terms of this model the decreasing of the second peak with the luminosity decreasing can be explained by the decreasing of the accretion column height and consequently by the obscuration of its colder parts ([8]).

Conclusions

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

– the strong pulse profile changes with the 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 by a complex manner.

REFERENCES

1. Basko M.M., Sunyaev R.A., 1976a, MNRAS, 175, 395
2. Gnedin Yu., Sunyaev R., 1973, A&A, 25, 233
3. Kreykenbohm I., Mowlavi N., Produit N., et al., 2005, A&A, 433, L45
4. Lyubarskii Yu., Sunyaev R., 1988, Sov. Astron. Lett., 14, 390
5. Meszaros P., Nagel W., 1985, ApJ, 299, 138
6. Pottschmidt K., Kreykenbohm I., Wilms J., et al., 2005, ApJ, 634, L97
7. Tsygankov S., Lutovinov A., Churazov E., Sunyaev R., 2006a, MNRAS, 371, 19
8. Tsygankov S., Lutovinov A., Sunyaev R., 2006b, in press

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