Strong outburst activity of the X-ray pulsar X Persei during 2001-2011

A. Lutovinov1*, S. Tsygankov2,3,1, M. Chernyakova4,5

1Space Research Institute of the Russian Academy of Sciences, Profsoyuznaya Str. 84/32, Moscow 117997, Russia
2Finnish Centre for Astronomy with ESO (FINCA), University of Turku, Väisäläntie 20, FI-21500 Piikkiö, Finland
3Astronomy Division, Department of Physics, FI-90014 University of Oulu, Finland
4Dublin City University, Dublin 9, Ireland
5Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland

Accepted .... Received ...

ABSTRACT
We present results of a comprehensive analysis of the X-ray pulsar X Persei over the period 1996 to 2011, encompassing the quite low state and subsequent strong outburst activity. Using data from the RXTE and Swift observatories we detected several consecutive outbursts, during which the source luminosity increased by a factor of ~ 5 up to $L_X \simeq 1.2 \times 10^{35} \text{erg s}^{-1}$. Previously the source was observed in a high state only once. The source spectrum in a standard energy band (4 – 25 keV) is independent of the flux change and can be described by a model that includes both thermal and non-thermal components. With the help of the INTEGRAL observatory data we registered the highly significant cyclotron absorption line in the source spectrum and, for the first time, significantly detected a hard X-ray emission from the pulsar up to ~ 160 keV. We also report drastic changes of the pulse period during the outburst activity: a long episode of spin-down was changed to spin-up with a rate of $\dot{P}/P \simeq -(3 - 5) \times 10^{-5}$ yr$^{-1}$, that is several times higher than previous rates of spin-up and spin-down. To search for a correlation between the X-ray and optical lightcurves we took data from the AAVSO International Database. No significant correlation between optical and X-ray fluxes at any time lag from dozens of days to years was found.

Key words: X-ray:binaries – (stars:)pulsars:individual – 4U 0352+309/X Persei

1 INTRODUCTION

4U 0352+309/X Persei is a classical persistent Be/X-ray binary system, consisting of an X-ray pulsar and a Be star companion optically identified with the star HD 24534. It was discovered during a high X-ray intensity state in 1972 (for simplicity below such high states are referred to as outbursts), when pulsations with a period of ~ 835 s were detected by the Copernicus observatory [White et al. 1976]. The distance to the source was estimated by different authors in the range of 700 to 1300 pc. In this paper we used the value of 950 ± 200 pc obtained by [Teling et al. (1998)]. Adopting this distance the source peak luminosity $L_X \simeq 2 \times 10^{35} \text{erg s}^{-1}$ in the 2 – 10 keV energy range was registered in 1975. The close proximity allowed the source to be observed in X-rays by different missions and experiments after 1978, despite its relative low luminosity $L_X \simeq (2 - 4) \times 10^{34} \text{erg s}^{-1}$.

For a long time X Persei was the only known persistent X-ray pulsar in Be-systems, until [Reig & Roche (1999)] pointed out the existence of a subclass of binaries with Be companions which harbor a slowly rotating neutron star and are characterized by a persistent low-luminosity X-ray emission and, probably, a long orbital period. Soon after, [Delgado-Marti et al. (2001)] succeeded in determining orbital parameters for X Persei and showed that the pulsar is in a moderately eccentric orbit ($e = 0.11$) with a $P_{\text{orb}} \simeq 250$ days orbital period. Recently, [Tsygankov et al. (2011)] reported a similarly long orbital period of $\simeq 155$ days for another X-ray pulsar RX J0440.9+4431, which belongs to this subclass as well.

Usually spectra of X-ray pulsars have an exponential cutoff at energies about ~20 keV (see, e.g., the recent review of [Filippova et al. 2003], and references therein). However results of the Ginga observatory gave evidence for the presence of a hard tail in the spectrum of X Persei above ~ 15 keV [Robba et al. (1996)]. Based on data of the BeppoSAX observatory, [Di Salvo et al. (1998)] showed that its broadband spectrum can be described by a combination of
the standard model and a power law with both high- and low-energy cut-offs, which dominates above ~ 15 keV. Later La Palombara & Mereghetti [2007] suggested that the thermal component with temperature of $kT > 1$ keV is typical for spectra of low luminosity, long period Be/NS binaries.

Similar to other accreting pulsars, the history of the X Persei pulse period shows episodes of both spin-up and spin-down. Previous to 1978 its spin history was erratic, with a general spin-up trend at a rate of $\dot{P}/P \simeq -1.5 \times 10^{-6}$ yr$^{-1}$. Since 1978 the neutron star has been spinning down with a similar rate $\dot{P}/P \simeq 1.3 \times 10^{-9}$ yr$^{-1}$ [Delgado-Marti et al. 2001]. Note that the spin-up episode in 1975-1978 coincided with the decay phase of the outburst.

Be stars are known to have a dense slow disk-like equatorial wind along with a low-density fast wind at higher latitudes. X Persei has shown large variations in optical and infrared brightness ($V = 6.1 - 6.8$, $K = 5.2 - 6.7$) and in the strength of the emission Balmer line (see, e.g. Roche et al. 1993; Telting et al. 1998; Clark et al. 2001, and references therein). These variations are usually interpreted as changes in the physical properties (density, geometry) of the Be star equatorial disk. The bright state of the star correlates with the presence of the emission lines and is evidence of the equatorial disk presence. At the same time, as it was mentioned by Telting et al. (1998), the strong variability seen in the optical and infrared is not reflected in the X-ray light curve. Particularly, the 1975 peak of the X-ray flux happened during the diskless state, while during the 1990 diskless state no X-ray brightening was observed. The absence of a direct correlation between the optical and X-ray light curves excludes the possibility that the neutron star is always accreting from the Be disc, probably due to the truncation of the disc (Clark et al. 2001). On the other hand the detailed study of the correlation between optical and X-rays was hampered by the absence of continuous measurements of the source flux in X-rays.

In this paper we present a comprehensive analysis of the properties of the X-ray pulsar X Persei over the period 1996 to 2011, encompassing the quite low state and subsequent strong outbursts activity. Thanks to the RXTE and Swift observatories, which have regularly monitored the whole sky in the last decades, we are able to look for the first time for a correlation between X-ray and optical data on a time scale from days to years. Moreover, based on data from the INTEGRAL and RXTE observatories we traced the evolution of the source pulse period and its spectral parameters during outbursts. We also used deep observations of the INTEGRAL observatory to detect for the first time a hard X-ray emission from the pulsar up to $\sim 160$ keV at a high significance level.

2 OBSERVATIONS AND DATA ANALYSIS

In this work we use data obtained with the RXTE (Bradt et al. 1993) and INTEGRAL (Winkler et al. 2003) observatories. In particular, we used data of the ASM/RXTE monitor to trace the long-term behavior of the X Persei flux in the soft energy band ($< 12$ keV). To compare it with the source behavior in hard X-rays we used observations of the IBIS/INTEGRAL and BAT/Swift telescopes (Gehrels et al. 2004). In the standard X-ray energy band (4 – 25 keV) data from the PCA/RXTE instrument (Obs. ID. 30099, 40424, 50404, 60067, 60068) were used to study the variability of the source spectrum and pulse period.

In 2003-2006 X Persei was in the field of view of telescopes of the INTEGRAL observatory only episodically. During deep observations of sky fields around the source in 2008-2010 the effective exposure of both X-ray telescopes of the observatory, JEM-X and IBIS/ISGRI, rose up to $\simeq 147$ ksec and $\simeq 3.7$ Ms, respectively. The reduction of the ISGRI detector data was done using recently developed methods described by Krivonos et al. (2010). The source spectrum from the JEM-X telescope was extracted with the standard OSA package version 9. For timing analysis the IBIS data was processed with the software developed and maintained in the National Astrophysical Institute in Palermo [1,2], a description of the data processing technique can be found in Mineo et al. (2006) and Segreto & Ferrigno (2007).

To build a complete picture of the secular variability of the X Persei pulse period we included in our analysis data from the XMM-Newton observatory that observed the source twice in Feb 2003 and Feb 2010 (Obs. ID. 0151380101 and 0600980101, respectively). Version 11.0 of the XMM-Newton Science Analysis System SAS was used to process the data.

The final spectral and timing analysis for all X-ray instruments was done using the standard tools of the FTOOLS/LHEASOF 6.7 package.

To search for a correlation between the source outbursts activity in X-rays and optics (V-band), we took data from the AAVSO International Database.

3 RESULTS

3.1 X-ray light curves

The X Persei light curve obtained with the ASM/RXTE monitor in 1996-2011 indicates that during the first years of observations the source intensity was low and relatively stable at the level of $\simeq 10$ mCrab, that corresponds to a luminosity of $L_X \simeq 2.3 \times 10^{34}$ erg s$^{-1}$ in the 2 – 10 keV energy band for the adopted distance (Fig.1). Such a level of intensity is typical for the normal (low) state of the pulsar, which had been observed since the end of 1970s (see, e.g. Roche et al. 1993; Telting et al. 1998, and references therein). In 2000-2001 the source flux began to steadily increase and reached a maximum ($\simeq 50$ mCrab) in May 2003. It then dropped very quickly (within 4-5 months) by a factor of two and stayed near this level until 2008, when it began to increase again. The source flux at the new maximum (May 2010) was approximately the same as the preceding one. And again it dropped very quickly by a factor of 2 (Fig.1).

The described source behavior at soft energies, as registered by the INTEGRAL (20-60 keV) and Swift (15-50 keV) observatories (Fig.1), almost completely mirrors the source.

1. http://isdc.unige.ch
2. http://www.pa.iasf.cnr.it/ferrigno/INTEGRALsoftware.html
3. http://www.aavso.org
variability in hard X-rays. The source outburst activity continued during 2011, when a third outburst with a slightly lower intensity was detected by the Swift observatory. A comparison of X-ray light curves of X Persei from Fig. 1 with the source long-term behavior reported by Roche et al. (1993); Telting et al. (1998) shows that a similar outburst activity was observed more than 35 years ago, in the middle of 1970s, with the Ariel V and Copernicus observatories. Moreover, the maximal flux from the source in 1975, was even slightly higher that measured in 2003 and 2010 and corresponded to a source luminosity of \( L_X \sim 2 \times 10^{35} \text{ erg s}^{-1} \) (Telting et al. 1998).

Besides these large outbursts with durations of years, the light curves of X Persei demonstrate a tentative variability with the amplitude of about 5 – 10 mCrab. To search for a possible correlation of these source intensity variations with the orbital phase, we folded ASM/RXTE and BAT/Swift light curves with a period of \( P_{\text{orb}} = 250.3 \) days (Delgado-Martí et al. 2001), but we did not find any significant deviations from the constant either in soft or in hard X-rays. Finally, note that the intensity rise, which has been very smoothly for several hundred days for all observed outbursts from X Persei, is non-typical for outbursts from usual transient sources (like black holes or transient X-ray pulsars). It can be connected with other mechanisms or processes responsible for the outburst activity in the source under investigation.

3.2 Pulse period evolution

The secular variability of the X Persei pulse period is presented in Fig. 2. It includes results of measurements taken from the literature and calculations performed in this work. The photon arrival times have been preliminarily corrected to the barycenter of the Solar System. After that the epoch folding method has been applied to determine the period of the pulsar. The errors in the period were estimated by the method briefly described by Filippova et al. (2004). To calculate them we performed an analysis of 10^3 simulated light curves. Data in each light curve were generated arbitrarily inside the error bars of the original data points. After that the best period for each simulated light curve was determined. Finally we computed the standard deviation of the best periods distribution and used this value as an estimation of the pulse period error.

Due to the faintness of the source and a relatively long pulse period (\( \sim 14 \) min) observations with an exposure of several hours (at least) are needed to determine the pulse period somewhat accurately. This was not a problem for INTEGRAL and XMM-Newton observations, where exposures were about several dozen ksec, but the typical duration of one RXTE observation is only several ksec. There-
before we grouped closely spaced RXTE observations into one set (when possible) and calculated the pulse period for each of them. Data of the XMM-Newton observatory were highly affected by event pile-up due to a very high count rate. Therefore in our analysis we used the same approach as La Palombara & Mereghetti (2007) and considered only data from the annulus area, excluding the central part of the source PSF. Applying the standard processing described in the SAS v.11 cookbook we determined the pulse period of X Persei: $838.52 \pm 0.20$ and $835.94 \pm 0.05$ sec for February 2003 and February 2010, respectively. The quality of the data during the last observation was much better than during the first one as its duration was longer ($\sim 31$ ksec vs $\sim 126$ ksec), therefore the corresponding uncertainty is lower. The obtained value of the pulse period in February 2003 is slightly lower than the value reported by La Palombara & Mereghetti (2007). There are two possible reasons for this difference: we used a more recent version of SAS, and we used the data from MOS cameras only. As mentioned by La Palombara & Mereghetti (2007) data of the pn camera were affected not only by photon pile-up, but during that observation the source flux was more or less close to a CCD gap. Finally, note that our value of the X Persei pulse period for February 2003 agrees well with the measurements from the INTEGRAL observatory, performed in April 2003 (see Fig.2).

Measurements from the INTEGRAL and XMM-Newton observatories indicate that sometime before the 2003 source flux maximum a deceleration of the neutron star rotation, which had lasted from 1978, changed to an acceleration (Fig.2). This repeats approximately the pulse period behavior during the outburst in 1974-1978, when the spin-up episode coincided with its declining phase, but started $\sim 400 - 500$ days after the luminosity maximum (Roche et al. 1993). The average spin-up rate since 2003 $P/P \simeq -3.6 \times 10^{-4}$ yr$^{-1}$ is higher than the one observed between 1974-1978. Moreover, measurements of the INTEGRAL observatory suggest the presence of something like a plateau in the pulse period history during the time interval MJD 53000 – 54500, when the source flux was more or less stable between the first and second outbursts. In such a case the pulsar is spinning-up only during outbursts with the even higher rate of $P/P \simeq -5 \times 10^{-4}$ yr$^{-1}$. The high spin-up rate can be probably connected with additional matter and angular momentum transfer to the neutron star due to the continuing source high state after the first outburst, and subsequent outbursts. This picture can be naturally explained in terms of the current theory of quasi-spherical accretion in low-luminosity X-ray pulsars (Shakura et al. 2012). In particular, the observed spin-up/spin-down transitions correlate with changes of the source luminosity, and their numerical values reflect the ratio of X-ray fluxes during spin-up and spin-down (see Fig.1 and eqs. 56-58 in Shakura et al. 2012). Moreover, the plateau at the pulse period history is apparently connected with the equilibrium state of the pulsar. Using the equation

$$P_{eq} \approx 10^3 \mu_{30}^{12/11} \dot{M}_{16}^{4/11} \left(\frac{P_{orb}}{10^3}\right)^4 v_8^4$$

where $P_{eq} \approx 837$ s is the equilibrium period, $\mu_{30}$ is the neutron star magnetic moment in units $10^{30}$ G cm$^3$, which can be calculated from the measured magnetic field (see below), $\dot{M}_{16}$ is the accretion rate in units $10^{16}$ g/s, deriving from the source luminosity, and $v_8$ is the relative wind velocity (in units $10^8$ cm/c), we can estimate $v_8$ as $\approx 200$ km/s, which agrees with measured or suggested values (see, e.g., Waters et al. 1985, Delgado-Marti et al. 2001).

As noted by Lutovinov et al. (2004), pulsations from the source are detected up to 100 keV. The pulse fraction increases from $\sim 30\%$ in the $2 - 10$ keV energy band to $\sim 60\%$ in the $20 - 60$ keV energy band, typical for X-ray pulsars (Lutovinov & Tsygankov 2004).

### 3.3 Evolution of the spectral parameters

Observations of X Persei with the PCA instrument of the RXTE observatory were performed several dozens of times in 2000-2003. They cover the low state and the rising phase of the first outburst very well. It allowed us to study a dependence of the source spectral shape variability on its intensity.

Using RXTE/PCA data we built a set of source spectra in the $4 - 25$ keV energy band and approximated them in a model that includes interstellar absorption, powerlaw and black-body components (\textit{wabs}, \textit{powerlaw} and \textit{bbodyrad} models in the \textit{XSPEC} package). Interstellar absorption in the direction of the source is quite low ($N_H = f_{cw} \times 10^{21}$) cm$^{-2}$ and cannot be determined correctly with the PCA instrument. It was fixed at the value of $N_H = 3.4 \times 10^{21}$ cm$^{-2}$ as measured by XMM-Newton (La Palombara & Mereghetti 2007). Dependencies of the black-body temperature $kT$, the radius of the emission surface of the thermal component $R$, the photon index $\Gamma$ and the normalization of the non-thermal component $A$ with time are shown in Fig.3 along with the changes of the source flux in the $2 - 20$ keV en-
ergy band, which was calculated from the best fit spectral models.

It is clearly seen that the photon index remains very stable during the whole period of observations and its value $\Gamma \approx 2$ is in a good agreement with broadband spectral measurements performed with the INTEGRAL observatory (see below). At the same time, the normalization of the non-thermal component $A$ increases with the source brightness by a factor of $3 - 4$. This increase is more significant in comparison with the extension of the emission surface of the thermal component from $R \approx 110$ m to $R \approx 150$ m that should lead to the increase in the relative contribution of the non-thermal component to the total source spectrum with the source brightening. But quantitatively this increase is practically negligible due to the simultaneous growth of the black-body temperature $kT$ from $\sim 1.6$ to $\sim 1.8$ keV (Fig.4), that in turn leads to the growth of the thermal component flux.

It is important to note that measured values of the thermal component parameters (black-body temperature and radius) agree with previous results of Coburn et al. (2001), but are different from the ones obtained with XMM-Newton (La Palombara & Mereghetti 2007) – the temperature is slightly higher, the radius is lower by a factor of two. This difference is due to the different energy bands of the observatories: $0.3 - 10$ keV for XMM-Newton and $4 - 25$ keV for RXTE. Naturally, the capabilities of the XMM-Newton observatory are much more suitable for a correct determination of quantitative characteristics of the thermal emission with temperatures of $kT \sim (1 - 2)$ keV. Therefore the RXTE data reflect only the qualitative behavior (relative changes) of its parameters as the source flux increases.

In addition to the long-term changes, the source X-ray flux demonstrates variability on the time scale of several days, which became especially significant (like flares) with the growth of the source average flux (Fig.2 from Delgado-Marti et al. 2001). Such flares are accompanied with the variability of the source spectral parameters, mainly its thermal component. Note that flares with changes of the spectrum hardness were observed earlier during the high luminosity states in 1970s (White et al. 1973, Frontera et al. 1973).

### 3.4 Hard X-ray emission and cyclotron line

X Persei was observed by the INTEGRAL observatory with a very long exposure in 2008-2010. Taking into account that 1) the source intensity didn’t change significantly during these observations (Fig.1 and that 2) the hard non-thermal spectral component is very stable even when the source flux is variable (see previous section), we could use all these data to reconstruct the broadband spectrum of X Persei. In the resulting spectrum, the signal from the source is significantly detected up to 160 keV (Fig.4a) for the first time. To date, hard X-ray emission at energies $> 100$ keV has been detected from only one other low luminosity X-ray pulsar RX J0440.9+4431 (Tsylvankov et al. 2012).

As a first step the source spectrum was approximated by the powerlaw model with a high-energy cutoff that is typical for X-ray pulsars (White et al. 1983). However this model gives an unacceptable value of $\chi^2 = 275$ for 45 d.o.f. Deviations of the measured spectrum from the model (Fig.1b) demonstrate a wide absorption feature near 30 keV, which can be interpreted as a cyclotron resonance absorption line and which was found earlier by Coburn et al. (2001) based on the RXTE data.

An additional component in the form of $gabs$ (XSPEC): $\exp\left(-\frac{\tau_{cycl}}{2\sigma_{cycl}}\right)\exp\left(-\frac{(E-E_{cycl})^2}{2\sigma_{cycl}}\right)$, improves the fit significantly to $\chi^2 = 58.2$ for 42 d.o.f. The resulting parameters of the cyclotron line – the line energy $E_{cycl} = 29.0 \pm 1.0$ keV and the line width $\sigma = 9.9 \pm 1.0$ keV – are in a good agreement with the results of Coburn et al. (2001), who also used the $gabs$ model. Using another suitable model $cyclabs$ (XSPEC): $\frac{-\tau_{cycl}(E-E_{cycl})^2}{(E-E_{cycl})^2 + \sigma_{cycl}^2}$ for the description of the cyclotron absorption line improves the fit even more to $\chi^2 = 43.7$ for 42 d.o.f. (Fig.1b): however the line energy is slightly lower in this fit ($\sim 23.5$ keV), typical for a cyclotron absorption line that is approximated by $gabs$ or $cyclabs$ models.

Thus, the parameters of the best-fit model (with the $cyclabs$ component), describing the broadband spectrum of X Persei in the $4 - 200$ keV energy range are: photon index $\Gamma = 2.05_{-0.04}^{+0.05}$, cutoff energy $E_{cut} = 69_{-2}^{+3}$ keV, folding

![Figure 4.](image)

For X Persei in the $4 - 200$ keV energy range, photon index $\Gamma = 2.05_{-0.04}^{+0.05}$, cutoff energy $E_{cut} = 69_{-2}^{+3}$ keV, folding
energy $E_{\text{fold}} = 3.40^{+1.0}_{-0.5}$ keV, line energy $E_{\text{cycl}} = 23.5^{+1.5}_{-1.4}$ keV, line width $\sigma = 13.4^{+1.4}_{-1.3}$ keV, line depth $\tau = 0.56^{+0.04}_{-0.05}$. Based on the measured value of the cyclotron line energy we can estimate the magnetic field on the neutron star surface as

$$B_{\text{NS}} = \frac{1}{\sqrt{1 - \frac{4GM_{\text{NS}}}{c^2R_{\text{NS}}}}} \frac{E}{11.6} \simeq (2.4 - 2.9) \times 10^{12} \text{G},$$

depending on the model used (gabs or cyclabs) and using $M_{\text{NS}} = 1.4 M_\odot$ and $R_{\text{NS}} = 15 \text{ km}$ (Suleimanov et al. 2011) for the neutron star radius and mass estimates, respectively. We expect that at the low luminosity of $\sim 10^{35} \text{ erg s}^{-1}$ the accreted matter is falling down to the neutron star surface, where most of the energy is released and the cyclotron absorption line is formed (see, e.g., Basko & Sunyaev 1974). Finally, it is important to note that the cyclotron line in X Persei was found to be significantly broader than typically observed in X-ray pulsars (Coburn et al. 2002, Filippova et al. 2005). The unusual broadness may be explained by insufficient knowledge of spectral continuum in the broad energy band. In particular, approximation of the spectrum with other components can lead to the artificial deficit of photons in the region where the spectral components overlap (see, e.g., Fig.8 in Di Salvo et al. 1998, or current paper of Doroshenko et al. 2012). This region roughly corresponds to the energy of the cyclotron line that can lead to the distortion of its parameters, particularly the width and depth of the line.

3.5 Correlation of X-ray and optical light curves

Since its discovery X Persei has been regularly observed in different wavebands. Particularly, it was found that long-term fluctuations in the optical brightness ($V \sim 6.7 - 6.1$) are accompanied by the cyclic variability in the peak ratio of H$_\alpha$ and HeI lines with periods varying between $\sim 1 - 10$ years (see Clark et al. 2001, and references therein). The optical variability of the source is usually interpreted as a change of the mass content and distribution in the circumstellar disk due to the presence of one armed density wave. The lack of correlation between the strength of the line and continuum emission demonstrates that the disk variability involves a redistribution of material within the disk, leading to changes in the radial density gradient (Clark et al. 2001).

Previous X-ray observations showed a number of cases when a rise of the optical brightness of the source wasn’t followed by a corresponding rise of the X-ray flux. This was explained by the truncation of the Be star decretion disk by the tidally-driven eccentric instability (see, e.g., Okazaki & Negueruela 2001). Truncation at the 3:1 resonant radius produces a wide gap between the disc outer radius ($0.47a_x$, $a_x$ is an orbital separation) and the periastron distance ($0.89 a_x$) (Clark et al. 2001). This wide gap depresses the accretion even at periastron, naturally leading to a low X-ray luminosity. In addition to this, Clark et al. (2001) report an episode of complete disc loss during the period 1988 May - 1989 June. The time needed for the outer radius disk to reach the truncation radius was estimated to be about $\sim 12(\alpha/0.2)^{-1} \text{ yr}$ after the disc formation begins ($\alpha$ is the Shakura-Sunyaev viscosity parameter, Shakura & Sunyaev 1973). Thus one can hardly expect any X-ray – optical correlation before the year 2000.

Regular monitoring of the system by ASM/RXTE since 1996 gives us a unique chance to test this hypothesis and to investigate the X-ray – optical dependance. Fig.5 shows the evolution of the system magnitude in V-band (upper panel) along with the X-ray evolution (bottom panel). It is clearly seen that the large variability of the source magnitude has only a weak reflection in the X-ray flux before 2002, when the rise of the optical flux is followed by a major outburst in X-rays. Given the discussion above, this rise in the X-ray flux can be interpreted as the interaction of the neutron star with the fully recovered disk. The maximum rise of the X-
ray flux in 2003 is followed by a rapid decrease to the level still two times higher than the pre-outburst level, while the optical flux stays at a rather high level until a small drop in 2010 and a subsequent rise in 2011. The drop of the X-ray flux in 2004 is probably related to the disruption of the outer layers of the disk, and the second rise of the X-ray flux is in good agreement with the estimated 5.7 years for the disk growth period (Clark et al. 2001).

In order to test qualitatively the correlation between optical and X-ray light curves with a possible non-zero time lag, we performed an interpolated correlation analysis using the improvements proposed by Gaskell & Peterson (1987) and White & Peterson (1994). In order to increase the statistic we have binned ASM/RXTE data into 10 day bins. The resulting Interpolated Cross-Correlation Function (ICF) is shown in Fig. These data show a tentative correlation between X-rays and optical flux with a zero time lag (with a correlation coefficient $R = 0.53 \pm 0.01$). The pronounced peaks at time lags of $\pm 1, \pm 2, \pm 3, \pm 4$ years are most probably artificial ones due to the internal ASM/RXTE periodicity related to the motion of Earth around the Sun (Wen et al. 2006) and also the sampling of the optical observations after 2003 (see Fig.7). These facts can also lead to the widening of the ICF, thus despite the quite large correlation coefficient we prefer to call this correlation a tentative one.

4 CONCLUSIONS

We presented here the comprehensive temporal and spectral analysis of the X-ray pulsar X Persei using data of the RXTE, INTEGRAL and XMM-Newton observatories. The main results can be summarized as:

- a strong outburst activity was detected from the source in soft and hard X-rays during 2001-2011. During this period the source luminosity twice reached its maximum for the last $\sim 30$ years, $L_X \simeq 1.2 \times 10^{35}$ erg s$^{-1}$;
- this activity was accompanied by drastic changes of the pulse period: a $\sim 35$-years period of the spin-down changed to spin-up with an average rate of $P/P' \simeq -3.6 \times 10^{-4}$ yr$^{-1}$, several times higher than previous rates of spin-up and spin-down; moreover, this acceleration of the rotation of the neutron star is apparently not in steady state, but depends on the source flux; the observed behaviour of the pulse period and its quantitative properties are naturally explained in terms of the current theory of the quasi-spherical accretion in low-luminosity X-ray pulsars (Shakura et al. 2012);
- at the same time, no significant variability of the spectral parameters with the source flux was found during the rising part of the first outburst in 2001-2003; the source spectrum in the $4-25$ keV energy band can be well described by a combination of a thermal component (with a temperature of $kT \simeq (1.6 - 1.8)$ keV) and non-thermal component (powerlaw with the photon index of $\Gamma \simeq 2$);
- using deep observations of the INTEGRAL observatory we reconstructed a broadband spectrum of X Persei in the $4-200$ keV energy range and, for the first time, significantly detected hard X-ray emission from the source up to $\sim 160$ keV;
- a significant detection of the cyclotron absorption line in the source spectrum allowed us to estimate the magnetic field strength on the neutron star surface as $B_{\text{NS}} \simeq (2.4 - 2.9) \times 10^{12}$ G depending on the model used (gabs or cyclabs);
- at the same time an insufficient knowledge of the spectrum continuum in the broad energy band can lead to distortion of the cyclotron line parameters (particularly its width and depth may be affected);
- the observed variations of the X-ray flux are in good agreement with predictions of the viscous decetration disk of the Be star (Clark et al. 2001), a quantitative study of the X-ray – optical cross-correlation shows only a tentative correlation with a zero time lag.

ACKNOWLEDGMENTS

Authors thank N.Shakura and K.Postnov for the discussion on results of the paper, and M.Tueller for the discussion on the details of the ICF method. This work was supported by the program “Origin, Structure and Evolution of the Objects in the Universe” by the Russian Academy of Sciences, grants NSh-5603.2012.2 from the President of Russia, grants 11-02-01328 and 11-02-12285-ofi-m-2011 from Russian Foundation for Basic Research, State contract 14.740.11.0611 and the Academy of Finland grant 127512. The research used the data obtained from the HEASARC Online Service provided by the NASA/GSFC, INTEGRAL Science Data Center and Russian INTEGRAL Science Data Center. The results of this work are partially based on observations of the INTEGRAL observatory, an ESA project with the participation of Denmark, France, Germany, Italy, Switzerland, Spain, the Czech Republic, Poland, Russia and the United States. We also acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research. AL and MC acknowledged the support from ISSI, Bern, where this work was partially done.

REFERENCES

Basko M.M., Sunyaev R.A., 1976, MNRAS, 175, 395
Bradt H.V., Rothschild R.E., Swank J.H., 1993, Astron. Astrophys. Suppl. Ser., 97, 355
Clark J.S., Tarasov A.E., Okazaki A.T., et al., 2001, A&A, 380, 615
Coburn W., Heindl W.A., Gruber D.E., et al., 2001, ApJ, 552, 738
Coburn W., Heindl W.A., Rothschild R.E., et al., 2002, ApJ, 580, 394
Delgado-Martí H., Levine A.M., Pehlh E., Rappaport S.A., 2001, ApJ, 546, 455
Di Salvo T., Burderi L., Robba N.R., Guainazzi M., 1998, ApJ, 509, 897
Doroshenko V., Santangelo A., Kreykenbohm I., Doroshenko R., 2012, A&A (accepted), arXiv:1202.6271
Filippova E.V., Lutovinov A.A., Shtykovskiy P.E., et al., 2004, Astron. Lett., 30, 824
Filippova E.V., Tsygankov S.S., Lutovinov A.A., Sunyaev R.A., 2005, Astron. Lett., 31, 729
Frontera F., Fuligni F., Morelli E., Ventura G., 1979, ApJ, 229, 291
Gaskell C.M., Peterson B.M., 1987, ApJS, 65, 1
Gehrels N., Chincarini G., Giommi P. et al., 2004, ApJ, 611, 1005
Haberl F., 1994, A&A, 283, 175
Krivonos R.A., Revnivtsev M.G., Tsygankov S.S., et al., 2010, A&A, 519, A107
La Palombara N., Mereghetti S., 2007, A&A, 474, 137
Lutovinov A.A., Grebenev S.A., Sunyaev R.A., Pavlinsky M.N., 1994, Astron. Lett., 20, 538
Lutovinov A.A., Tsygankov S.S., Revnivtsev M.G., et al., 2004, Proceedings of the 5th INTEGRAL Workshop The INTEGRAL Universe, ESA SP-552, 253
Lutovinov A.A., Tsygankov S.S., 2009, Astron. Lett., 35, 433
Mineo T., Ferrigno C., Foschini L., et al., 2006, A&A, 450, 617
Nagase F., 1989, PASJ, 41, 1
Okazaki A.T., Negueruela I., 2001, A&A, 377, 161
Reig P., Roche P., 1999, MNRAS, 306, 100
Robba N.R., Burderi L., Wynn G.A., et al., 1996, ApJ, 472, 341
Roche P., Coe M.J., Fabregat J., et al., 1993, A&A, 270, 122
Segreto A., Ferrigno C., 2007, in Proc. of the 6th INTEGRAL Workshop The Obscured Universe, ESA SP-662, 633
Shakura N.I., Sunyaev R.A., 1973, A&A, 24, 337
Shakura N., Postnov K., Kochetkova A., Hjalmarsdotter L., 2012, MNRAS, 420, 216
Suleimanov V., Poutanen J., Revnivtsev M., Werner K., 2011, ApJ, 742, 122
Telting J.H., Waters L.B.F.M., Roche P., et al. 1998, MNRAS, 296, 785
Tsygankov S.S., Lutovinov A.A., Krivonos R.A., 2011, Astron. Telegram, 3137
Tsygankov S.S., Krivonos R.A., Lutovinov A.A., 2012, MNRAS (accepted), arXiv:1201.0616
Wen L., Levine A.M., Corbet R.H.D., Bradt H.V., 2006, ApJSS, 163, 372
Waters L.B.F.M., van den Heuvel E.P.J., Taylor A.R., Habets G.M.H.J., Persi P., 1988, A&A, 198, 200
White N.E., Mason K.O., Sanford P.W., Murdin P., 1976, MNRAS, 176, 201
White N.E., Swank J.H., Holt S.S., 1983, ApJ, 270, 711
White R.J., Peterson B.M., 1994, PASP, 106, 879
Winkler C., Courvoisier T.J.-L., Di Cocco G., et al., 2003, A&A, 411, L1