Search for photon bubble oscillations in V0332+53

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ABSTRACT

We report results of our search for fast oscillations in lightcurve of one of the brightest accretion powered pulsars on the sky V0332+53 with the help of data of the PCA spectrometer of the RXTE observatory. In course of this search we have carefully explored complications appearing if one uses only sub-bands of the total bandpass of the PCA spectrometer. We show that lightcurves collected in the soft sub-band of the PCA spectrometer contains an additional instrumental noise, lightcurves of harder sub-bands lack some fraction of the anticipated Poisson noise. We show that this noise is caused by a cross-talk of energy bands, which lasts up to ∼ 200 µsec. One hypothesis is that these effects are caused by temporarily drop of the PCA detector gain after any occurred event due to slowly moving ions in the detector volume. In order to avoid this effect we searched for fast oscillations in flux of V0332+53 only in the total bandpass of the PCA spectrometer 2-60 keV. We have not detected any quasi-periodic oscillations in lightcurve of the source with an upper limit at the level of 0.5% in the Fourier frequency range 200-1500 Hz.

Key words: accretion, accretion discs, X-rays: binaries – stars: individual: Sco X-1 – stars: individual: V0332+53

1 INTRODUCTION

Binary systems with a compact object are among the brightest sources in galaxies, in particular in the X-ray energy range. Their bolometric luminosity is powered by accretion onto relativistic objects like neutron star (NS) or black hole (BH). Luminosity of black hole accretors is produced by accretion disks (Shakura & Sunyaev 1973; Pringle & Rees 1972), while neutron star accretors have additional structures on their surfaces. In case of non magnetic neutron stars it is a boundary/spreading layer, in which rapidly rotating matter of the accretion disk decelerate to neutron star rotational velocity (e.g. Hoshi 1984; Sunyaev & Shakura 1986; Inogamov & Sunyaev 1999). If the neutron star is strongly magnetized, then the accretion flow can not continue undisturbed till the neutron star and is channelled to neutron star magnetic poles (Lamb, Petrich, & Pines 1973; Davidson & Ostriker 1973).

In case of actively accreting neutron stars the falling matter is stopped near the NS surface due to pressure of outgoing radiation (Basko & Sunyaev 1976; Braun & Yahel 1984; Lyubarskii & Sunyaev 1988). In a set of papers it was shown that the settling of the infalling flow to the NS surface might be unstable with respect to presence of so-called photon bubbles – the regions with high radiation pressure act like light fluid with respect to heavy fluid of infalling plasma (see e.g. Arons 1992; Klein et al. 1996a). It was predicted that these oscillations might be visible in time series of X-ray luminosity of such sources. Depending on the area of the accretion column footprint estimates of the characteristic timescales varied from hundreds of Hz to several kHz (Klein et al. 1996a; Jernigan, Klein, & Arons 2000).

Launch of the orbital observatory Rossi XTE (Bradt, Rothschild, & Swank 1993) have provided a tool to search for these predicted features. The PCA spectrometer of RXTE observatory had the largest collecting area of all previous X-ray orbital instruments (it was switched off on Jan.5, 2012) and indeed allowed to discover a lot of new fast phenomena (see e.g. van der Klis 2006). Among them there were claims about detection of photon bubbles oscillation (Klein et al. 1996b; Jernigan, Klein, & Arons 2000).

In this paper we are trying to obtain the best possible constrains on presence of a rapidly (at Fourier frequency scales around kHz) variable noise component in lightcurves of accretion powered X-ray pulsars. As an example we study one of the brightest source of this type V0332+53.

2 DATA ANALYSIS

In our search we use data of the PCA spectrometer (Jahoda et al. 2006) of the RXTE observatory (Bradt, Rothschild, & Swank 1993).

The most straightforward way to search for quasi-
periodic oscillations is to study power density spectra of original lightcurves of X-ray sources, calculated as square of amplitude of their Fourier transform (Leahy et al. 1983):

$$ P_j = \frac{2|a_j|^2}{N_j} \quad (1) $$

where, $|a_j|$ - amplitude of the Fourier transform of the curve at Fourier frequency $j/T$, $N_j$ - number of photons within the transformed lightcurve segment of length $T$. Due to limited number of photons from X-ray sources, variability of a signal at the highest Fourier frequencies is always dominated by Poisson noise. In the abovementioned normalization the level of Poisson noise to be seen by an ideal instrument is 2.0 [Leahy et al.] (1983).

### 2.1 Power spectra from PCA data and effects of deadtime

In the case of a real instrument, this counting noise of photons is modified by a number of instrumental effects. PCA is a gas proportional counter, consisting of 5 independent units (Proportional Counter Units - PCUs) each with its own electronics. All events, which trigger the low level discriminator initiate a sequence of analog-to-digital conversions, during which the detector is busy – the detector is deadtime-locked. All units count X-ray photons, but also count a large flux of background events, created by charged particles. Charged particles typically create events at more than one set of the PCU anodes and thus a large fraction of them can be vetoed using anti-coincidence logic. This explicitly means that the "good counts" is only a fraction of total counts, measured by instrument. In case of bright sources the fraction of good counts is large but still less than unity.

In addition to simple background events PCUs also have so called Very Large Events – events, which deposit more than $\gtrsim 75$ keV of energy into the PCU volume. These events saturate PCU analogue amplifiers and in order to resume normal operation of the detector, the whole PCU is intentionally disabled for some pre-set time period. Typical settings, which can be found in scientific data is daVle=1 and daVle=2. Exact values of these VLE dead-times during the flight of RXTE/PCA were measured by different methods to be approximately 50-70 $\mu$sec and 140-170 $\mu$sec correspondingly [Zhang et al. 1995; Jernigan, Klein, & Arons 2000; Revnivtsev, Gilfanov, & Churazov 2000; Wei 2006; Jahoda et al. 2006].

Effects of modification of pure Poisson noise in data of RXTE/PCA were identified in a number of works (see e.g. Zhang et al. 1995, 1996; Morgan, Remillard, & Greiner 1997; Jernigan, Klein, & Arons 2000; Revnivtsev, Gilfanov, & Churazov 2000; Wei 2006). It was shown that the main predicted effects of timing logic of PCA detector chains on Poisson noise of counts are indeed seen in real data, but it is exceedingly hard to calculate exact corrections from the first principles and some recorded housekeeping count rates. Thus, in some works it was adopted to use an analytic model of deadtime-modified Poisson noise and fit its parameters to real power spectra (Jernigan, Klein, & Arons 2000; Sunyaev & Revnivtsev 2000; Revnivtsev, Gilfanov, & Churazov 2000). This approach uses assumption that at high frequencies (typically above kHz) there is no intrinsic variability of flux of real sources and all recorded variability is due to modified Poisson process.

It was shown that modification of the Poisson noise in total PCA bandpass due to simple deadtime effect and effect of occasional switch-offs due to Very Large Events can be adequately described by formulas (see e.g. Jahoda et al. 2006):

$$ P(f) = 2 - P_1 - P_2 \cos(2\pi b t) + P_3 \left( \frac{\sin(\pi t_vle f)}{\pi t_vle f} \right)^2 \quad (2) $$

$$ P_1 = 4 r_0 t_d \left( 1 - \frac{t_d}{2t_b} \right) $$

$$ P_2 = 2 r_0 t_d \frac{N - 1}{N} \frac{t_d}{t_b} $$

$$ P_3 = 2 r_0 v_{dle} t_{dle}^2 $$

where $t_d \sim 8 - 10 \mu$sec – deadtime of the instrument per event, $t_vle$ – deadtime of Very Large Event, $t_b$ – bin time of the lightcurve, $r_0$ – average count rate in the lightcurve, $N$ – number of frequency bins in the Fourier transform. In these formulas all count rates are written for single detector. Example of application of these formulas to power spectrum of the brightest source on X-ray sky Sco X-1 is shown in Fig.1. For this plot we have used observation Obs-ID 10059-01-03-00, count rate of the source is $\sim 77.5$ kcnts/sec/5PCU, exposure time 1.04 ksec. We adopted here $t_{dle} = 76 \mu$sec (Revnivtsev, Gilfanov, & Churazov 2000). It is seen that quality of this analytic fit is very good: $\chi^2 = 62.2$ for 55 degrees of freedom at power density values at Fourier frequencies above 400 Hz.

### 2.2 Modifications of power spectra in PCA energy sub-bands

In works of Revnivtsev, Gilfanov, & Churazov (2000; Wei 2006) it was noted that apart from above-mentioned modifications of Poisson noise in real data some additional modifications are revealed in power density spectra calculated from...
data in sub-bands of RXTE/PCA. In particular, the most striking feature is an appearance of an additional noise at frequencies up to 1-1.5 kHz in lightcurves, constructed from data at lowest energy ranges of PCA (e.g. channels range 0-13 or 0-17 out of 256 channels of PCA).

As an illustration of this effect we present power spectra of the brightest X-ray source on the sky Sco X-1 from a set of observations ID 96443-03-01-[00,...,13], 96443-03-02-00 (time resolution 2–14 sec ~ 61µsec), total exposure time ~ 9.5 ksec. We have calculated power spectra for three energy bands: channels 0-17 (<7 keV, count rate ~75 kcnts/sec/5PCU), 18-35 (~7-15 keV, count rate ~28 kcnts/sec/5PCU) and 0-249 (total energy range of PCA 2-60 keV, count rate ~103.7 kcnts/sec/5PCU). The VLE deadtime setting during these observations is the same (dsVle=1) as during observation, shown in Fig[4]

It is seen that while the total band (channels 0-249) power density spectrum is indeed similar to that on Fig[4] (apart from different time binning and somewhat larger source count rate), the power density spectra from sub-bands (channels 0-17, channels 18-35) are strongly different from that.

It is likely that the origin of these peculiarities is related to physics of detection of X-ray photons in a gas proportional counter. In work of [6] (2006) it was proposed that this effect might be caused by temporarily drop of the detector gain over some part of the detector volume immediately after any occurred event. All events depositing energy into detector volume, create a cloud of electron-ion pairs. Electrons drift to the nearest anode and there create an avalanche. Electrons born in this avalanche are rapidly absorbed by the anode, but much slower ions drift to the respective cathode. During their drift time they can screen the electric field for subsequent events and thus effectively reduce the detector gain. Events, occurred during time periods, when ions from the previous event are drifting towards the cathode, will have slightly lower pulse heights/ascribed energies. Thus, any event, which occurred in the detector volume causes temporarily small drop of the gain in this volume.

It means that events, occurred near the boundary between softer and harder bands will be able to switch from harder band to softer band if they will come during this "floating boundary" time period. Temporarily drop of the detector gain squeeze the energy scale of the instrument. Therefore only hard energy bands can loose counts. The softest energy band does not loose counts, but rather gather counts from neighbouring harder energy band.

In order to check presence of this effect in real data we have calculated cross correlations between light curves of Sco X-1 in three non-overlapping energy bands (the same data as used for Fig[2]). If there would be no "cross-talks" between counts in these energy channels apart from ordinary dead-time effect due to detector electronics we should not expect to see any effects on delays $\tau > |t_d| \sim 8 - 10 \mu sec$. In fact we do see very strong correlation of these signals up to delays < 300 µsec (Fig[3]), where intrinsic variability of the source is absent.

Top panel of Fig[3] shows cross-correlation between energy bands determined by PCA channels 0-17 and 18-35, bottom panel - between 18-35 and 36-249. We see that after any recorded event (zero lag) there is a gap at positive delays during ~300 µsec, i.e. the hard band count rate is lower than it should be. We see these missing events at negative delays – they switched to be in the soft band. The effective timescale for this "floating boundary" window is approximately ~200 – 300µsec. The amplitude of the peak at negative delays (and amplitude of the gap at positive delays) should depend on the fraction of counts, which appear as additional to the original counts in the soft energy band for the "extended ion drift time" period.

Crosscorrelation of light curves in harder energy bands (Fig[3] lower panel) looks a bit different. We also see a gap at positive delays – switching of fraction of harder band photons into softer band, but at the same time we also see a gap at negative delays. This happens because during finite
time period after any event the count rate in this band (in our case channels 18-35) was increased by some fraction of counts from harder band (channels 36-249), but at the same time much larger fraction of counts moved from this band to even softer band (channels 0-17), thus in total this energy band still loose some fraction of its counts.

The characteristic time scale of the noted effective change of the energy band boundaries can be estimated from cross-correlations: a gaussian fit gives approximately \( t_{\text{drift}} \sim 160 - 170 \mu \text{sec} \) (see Fig.3). It should be compared to the time of drift of ions in PCU volume. Xenon ion mobility is approximately 0.8 cm\(^2\) sec\(^{-1}\) V\(^{-1}\) (e.g. Tables of Physical & Chemical Constants, Kaye & Laby Online, www.kayelaby.npl.co.uk). For the applied voltage \( \sim 2.5\) kV/cm the ions drift velocities is \( \sim 2\) cm/msec. The distance between anodes and cathodes is approximately 0.6-0.7 cm (the total thicknes of PCU layers is approximately 1.3 cm, Jahoda et al. [2006]), therefore the drift time is approximately \( \sim 300\) µsec. This estimate is broadly consistent with the timescale, which we inferred from analysis of cross-correlations.

Therefore we do see that the PCA scheme of readout of events into separate energy bands have relatively long relaxation time and thus lightcurves of sources, recorded in these energy bands are mutually distorted.

2.3 Simulations

We have simulated the abovementioned effect.

We have simulated pure Poisson noise of photons and selected only those, which were separated by more than non-paralizable deadtime \( t_d = 10\)µsec. For all events we have simulated the energy (channel), according to spectral energy distribution of Sco X-1, recorded in ObsIDs 96443-03-... We have adopted the intrinsic source count rate 20 kcnts/sec/PCU in total energy range (which gives 100 ksec/sec/5PCU, PCA spectrometer has 5 independent detector units).

We have not simulated the VLE deadtime effect.

In order to imitate the temporarily shift of boundaries between energy bands we have assumed that any incoming event with some predefined probability to cause a change of the energy scale of the instrument (gain). We assumed that the depth of the gain drop depends on energy of the event. The energy scale (gain) dependence on time since that event \( (dt) \) was assumed to be:

\[
G(dt) = 1 - 0.15 \left( \frac{E}{7\text{keV}} \right) \exp \left[ -\frac{1}{2} \left( \frac{dt}{t_{\text{drift}}} \right)^2 \right]
\]

, here the ion drift time \( t_{\text{drift}} = 170\)µsec, \( dt \) – time between current event and that caused the gain drop. The final energy channel of the event is \( ch_f = ch_i G \). The resulted event list was split into three energy bands 0-17, 18-35 and 36-249.
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Figure 7. Power spectrum of the Sco X-1 lightcurve in the channel band 0-17 (< 7 keV). Solid lines show the best fit model to the modified Poisson noise in the lightcurve. Contribution of noise due to "floating boundary effect" is illustrated by a dashed curve, it is approximated by a zero-centered gaussian with characteristic width \( f_0 \sim 1060 \text{ Hz} \).

Power spectra of lightcurves (total exposure time 20 ksec) obtained in this way in channels 0-17 and 18-35 are shown in Fig. 5. Crosscorrelations of obtained lightcurves are shown in Fig. 6.

Additional component that one can see at power spectrum collected in channel range 0-17 can be approximated by a zero-centered gaussian:

\[
P_t \propto \exp \left[ -\frac{1}{2} \left( \frac{t}{f_0} \right)^2 \right]
\]

with characteristic width \( f_0 = 1043 \pm 20 \text{ Hz} \).

Example of approximation of the power spectrum of Sco X-1 soft band lightcurve (channels 0-17) by models of dead-time modified Poisson noise, i.e using formulas (2) including effect of VLE deadtime and effect of the "floating boundary noise" (3), is shown in Fig. 7. The effect of "floating boundary" can be approximated by a zero-centered gaussian with \( f_0 = 1060 \pm 70 \text{ Hz} \).

2.4 Cen X-3

One of the results, which might be affected by the abovementioned instrumental feature is the detection of a continuum noise around kHz in bright X-ray pulsar Cen X-3. In work of Jernigan, Klein, & Arons (2000) it was shown that power spectrum of the Cen X-3 lightcurve, recorded by PCA in the soft energy band (channels 0-17, which corresponds to energies < 7 keV) demonstrates broad kilohertz continuum (possibly with two quasi-periodic oscillations). Shape of this noise component was estimated by fitting formulas (2) to the data at Fourier frequencies above 2 kHz. Dashed curve is a contribution of non VLE-deadtime components.

The energy spectrum of Cen X-3 is strongly different from that of Sco X-1. As the number of counts which are

when the source was not eclipsed (count rate in the channel range 0-17 is more than 700 cnts/sec/5PCU). This gives us an exposure time \( \sim 208 \text{ ksec} \). The power spectrum in the channel range 0-17 (Fig. 8) was constructed over 16 sec segments (2\(^{18}\) time bins with \( t_b \approx 61\mu\text{sec} \)) and then averaged and binned into logarithmically spaced bins.

In order to demonstrate the importance of effect of "floating boundary noise" for case of Cen X-3 we have repeated the analysis of Jernigan, Klein, & Arons (2000). We have selected the same dataset (ObsIds 20104-01-01-..., taken on Feb 28.-Mar.3, 1997), and used only time periods
able to switch between energy bands depends on the shape of the spectrum we need to make another simulation of the effect of the ion-drift time on power spectra of the source lightcurves.

The energy spectrum of the source was taken from real data (see Fig. 7). Power spectrum of the simulated lightcurve in the channel range 0-17 is presented in Fig. 10. Simulation was performed with the same setup as for Sco X-1 but with lower count rate. The adopted intrinsic count rate of the source in the total energy band is \(t_{\text{ConX-3}} = 770\) cnts/sec/PCU.

The resulted power spectrum of a simulated lightcurve (the channel range 0-17, total simulated exposure time \(\sim 518\) ksec) is shown in Fig. 10.

It is seen that the "floating boundary" effect creates an increase of variability power exactly at the place where it was seen by Jernigan, Klein, & Arons (2000). Therefore we should conclude that the increased noise in signal from Cen X-3 at frequencies above 100 Hz can be interpreted in terms of the described instrumental effect.

As an additional (but not decisive) argument in favour of artificial nature of this signal one can mention that the signal (broad kHz continuum) was not detected in higher energy band (\(\sim 7 - 15\) keV), while the average count rate in this band is similar to that in the soft band and typically the amplitude of all QPO-like features does not decrease with energy.

3 SEARCH FOR PHOTON BUBBLE OSCILLATIONS IN V0332+53

Accreting X-ray pulsar in the binary system V0332+53 (Terrell & Priedhorsky 1983) is one of the brightest sources of this class in our Galaxy. The RXTE observatory have performed a number of observations of this source (e.g. Tsygankov et al. 2006) with total exposure more than 500 ksec.

In order to obtain the best possible sensitivity to fast oscillations in lightcurve of the source we have selected only time periods, when the total count rate recorded from the source by PCA is larger than 4000 cnts/s/5PCU and analysed only data with time resolution not worse than \(\sim 122\) \(\mu\)sec. In order to avoid problems with the PCA energy sub-bands (described above) we have used combined data over all PCA energy channels (0-249).

In total it gives us approximately 113 ksec of observations with VLE deadtime setting \(ds_{\text{Vle}}=1\) (average count rate \(\sim 7.2\) cnts/sec/PCA) and approximately 53 ksec with VLE deadtime setting \(ds_{\text{Vle}}=2\) (average count rate \(\sim 6.2\) cnts/sec/PCA). The resulted power spectra are shown in Fig. 11.

We have fitted the obtained power spectra in frequency range 20-4096 Hz with a model, consisting of deadtime-modified Poisson noise (formulas (2)) and a power law. We see that the quality of fits is good, \(\chi^2\) values are 58.8 and 79.2 for 60 degrees of freedom for power spectra with VLE deadtime settings \(ds_{\text{Vle}}=2\) and \(ds_{\text{Vle}}=1\) respectively. During fits we have fixed the VLE deadtime at values 150 \(\mu\)sec (\(ds_{\text{Vle}}=2\)) and 76 \(\mu\)sec (\(ds_{\text{Vle}}=1\)).

We clearly see a power law up to the Fourier frequencies 100-200 Hz (similar to Jernigan, Klein, & Arons 2000), but no quasiperiodic oscillations or other components, which are different from instrument-modified Poisson noise. The 2\(\sigma\) upper limit on the Lorentzian QPO with quality factor 4 (i.e. \(f/\Delta f = 4\)) is approximately 0.4-0.75% over the Fourier frequency range 200-1500 Hz.

Absence of some additional noise component (apart from a power law continuing from lower Fourier frequencies) at Fourier frequencies below 1 kHz allows us to make some conclusions about properties of the accretion column. According to calculations of Klein et al. (1996a) Jernigan, Klein, & Arons (2000) photon bubble oscillations appear below 1 kHz timescales only if polars caps have relatively large fractional area, \(> 10^{-6}\) of the total area of the neutron star surface. If the fractional area of the accretion column is smaller than that the typical frequencies of photon bubble oscillations were predicted to be above kHz.

Therefore, in the framework of calculations of Klein et al. (1996a) we can conclude that the fractional area of the accretion column footprint on the NS surface is smaller than \(< 10^{-5}\). It is interesting to mention that indications that the area of the accretion column footprint on NS surfaces can be as small as \(< 10^{-6}\) were demonstrated in work of Semena et al. (2014) from completely different physical effect. Basing on upper limit on the plasma cooling time in the accretion column near magnetic white dwarf it was shown that area of the accretion column footprint is smaller than \(< 10^{-3}\) of the WD surface. Such a small fractional area is a result of small geometrical thickness of accretion flow on top of the magnetospheric surface. Extrapolating the matter flow lines (as lines of force of a dipole magnetic field) to typical radii of NSs authors obtained the abovementioned estimate.
4 SUMMARY

We have studied the power density spectra of bright X-ray sources, measured with RXTE/PCA with the aim to obtain the best constrains on presence of fast (~ kHz) noise components in lightcurves of accretion columns on magnetized neutron stars.

- We have demonstrated that separation of RXTE/PCA counts into sub-bands creates distortions in their noise properties. We showed that behavior of sub-band lightcurves can be explained if all events, registered by RXTE/PCA create a sudden slight drop in detector gain, which redistribute counts, registered by PCA between energy sub-bands. The soft sub-band gain additional counts, harder energy sub-bands loose counts.
- Crosscorrelations between lightcurves in different energy sub-bands show that this gain returns to the original state at gaussian time scale ~ 170 µsec. One of possible explanations of this effect is a screening of the electric field in the detector volume by slowly moving ions created by previous event.
- We have simulated this effect and obtained reasonable agreement with observed behavior of sub-bands power spectra of lightcurves of sources Sco X-1 and Cen X-3.
- We have calculated power density spectra of one of the brightest accretion powered magnetized neutron star (pulsar) V0332+53. Avoiding the abovementioned problem with the PCA energy sub-bands we have used lightcurves of the source only in the total PCA energy bandpass. We have not detected any quasiperiodic oscillations in the Fourier frequency range 200-1500 Hz with upper limits 0.4-0.5%.
- In the framework of photon bubble oscillations in accretion column of magnetized neutron stars, their absence at frequencies below 1 kHz might indicate that the fractional area of footprints of the accretion column on the NS surface is small, below 10^{-3}.

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REFERENCES

Arons J., 1992, ApJ, 388, 561
Basko M. M., Sunyaev R. A., 1976, MNRAS, 175, 395
Blum W., Rierler W., Rolandi L., 2008. "Particle detection with drift chambers", Springer, ISBN: 978-3-540-76683-4
Bradt H. V., Rothschild R. E., Swank J. H., 1993, A&AS, 97, 355
Braun A., Yahel R. Z., 1984, ApJ, 278, 349
Davidson K., Ostriker J. P., 1973, ApJ, 179, 585
Jahoda K., Markwardt C. B., Radeva Y., Rot A. H., Stark M. J., Swank J. H., Strohmayer T. E., Zhang W., 2006, ApJS, 163, 401
Hoshi R., 1984, PASJ, 36, 785
Inogamov N. A., Sunyaev R. A., 1999, AstL, 25, 269
Jernigan J. G., Klein R. I., Arons J., 2000, ApJ, 530, 875
Klein R. I., Jernigan G., Klein R. I., Arons J., Morgan E. H., Zhang W., 1996, ApJ, 469, L119
Lamb F. K., Petrick C. J., Pines D., 1973, ApJ, 184, 271
Leahy D. A., Darbro W., Elsner R. F., Weisskopf M. C., Kahn S., Sutherland P. G., Grindlay J. E., 1983, ApJ, 266, 160
Lyubarskii Y. E., Syunyaev R. A., 1988, SvAL, 14, 390
Morgan E. H., Remillard R. A., Greiner J., 1997, ApJ, 482, 993
Pringle J. E., Rees M. J., 1972, A&A, 21, 1
Revnivtsev M., Gilfanov M., Churazov E., 2000, A&A, 363, 1013
Semena A. N., et al., 2014, MNRAS, 442, 1123
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Syunyaev R. A., Shakura N. I., 1986, SvAL, 12, 117
Sunyaev R., Revnivtsev M., 2000, A&A, 358, 617
Terrell J., Friedhorsky W. C., 1983, BAAS, 15, 979
Tsygankov S. S., Lutovinov A. A., Churazov E. M., Sunyaev R. A., 2006, MNRAS, 371, 19
van der Klis M., 2006, In: Compact stellar X-ray sources. Edited by Walter Lewin & Michel van der Klis. Cambridge Astrophysics Series, No. 39
Wei Dennis, MIT thesis, 2006
Zhang W., Jahoda K., Swank J. H., Morgan E. H., Giles A. B., 1995, ApJ, 449, 930
Zhang W., Morgan E. H., Jahoda K., Swank J. H., Strohmayer T. E., Jernigan G., Klein R. I., 1996, ApJ, 469, L29