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ASTRONOMY AND ASTROPHYSICS

Fourier power spectra at high frequencies: a way to distinguish a neutron star from a black hole

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Abstract. We analyzed the power density spectra of a sample of 9 neutron star and 9 black hole binaries in the low/hard spectral state. In the power density spectra of accreting neutron stars with a weak magnetic field a significant power is contained at frequencies close to one kHz. At the same time, most Galactic accreting black holes demonstrate a strong decline in the power spectra at the frequencies higher than 10–50 Hz. We propose to use this empirical fact as a method to distinguish the accreting neutron stars from black holes in X-ray transients. The X-ray transients that demonstrate significant noise in their X-ray flux at frequencies above ~ 500 Hz should be considered neutron stars. We propose to explain the observed difference as a result of the existence of a radiation dominated spreading layer on the neutron star surface (Inogamov& Sunyaev 1999). The possible very high frequency variabilities of this layer are discussed.

Key words: Accretion, accretion disks – Instabilities – Stars:binaries:general – Stars:fundamental parameters – Stars:neutron – X-rays: general – X-rays: stars

1. Introduction

Among the Galactic X-ray sources black holes (BH) distinguish themselves by the shape of their X-ray spectrum (see e.g. Tananbaum et al. 1972, Sunyaev & Truemper 1979, White, Kaluziensky & Swank 1984, Tanaka & Shibazaki 1996). In the low spectral state BHs emit a significant part of their luminosity at energies of hundreds keV (see e.g. Sunyaev et al. 1991), while neutron stars (NS) radiate much smaller part of their total luminosity in this energy range (see e.g. Barret et al. 2000). A soft component that is present in the spectra of BH binaries in the high(soft) state has a characteristic temperature which can be significantly lower than that in the spectra of NS binaries with similar luminosity. Besides, the BH binaries in this soft spectral state demonstrate a hard power law tail (likely without a high energy cutoff up to 500-600 keV, see e.g. Sunyaev et al. 1988, 1992; Kroeger et al. 1996), whereas bright accreting NSs have never yet shown such spectra (e.g. Tanaka & Shibazaki 1996). These spectral properties were frequently used as a criterion to determine the nature of the compact object. We will not discuss here the widely accepted methods of establishing neutron star systems through the presence of pulsations or X-ray bursts. The detection of coherent pulsations indicates the presence of the strong magnetic field and rotation of the NS. X-ray bursts (type I) demonstrate that nuclear explosions occur in the matter that was collected at the surface of the NS during the accretion. However there is a significant number of sources, mostly transients, for which neither X-ray pulsations nor X-ray bursts have been observed. Below we propose another method of determining the nature of the compact object based on its power density spectrum (PDS) at the high frequencies f>10–100 Hz.

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2. Observations and data analysis

We used the publicly available data of the Proportional Counter Array (PCA) aboard the Rossi X-ray Timing Explorer (RXTE) obtained in 1996–1998. We chose the observations of X-ray binaries in the low/hard spectral state with $L_{\rm x} \sim 10^{36} - 10^{37}$erg/s $\sim 0.01 - 0.1 L_{\rm crit}$, where $L_{\rm crit}$ is the critical Eddington luminosity, made in 1996-1998. We only used the data when all 5 Proportional Counter Units (PCUs) were operational. The count rates for the sources vary from a few hundreds counts/sec/PCA to several thousands counts/sec/PCA for both NS and BH sources. Our sample of NS and BH binaries is presented in Table 1.

We constructed the power density spectra of the X-ray sources using $\sim$244 μsec (2^{-12} sec) time resolution light curves divided into parts containing 8192 bins. The obtained PDSs were normalized to the square of

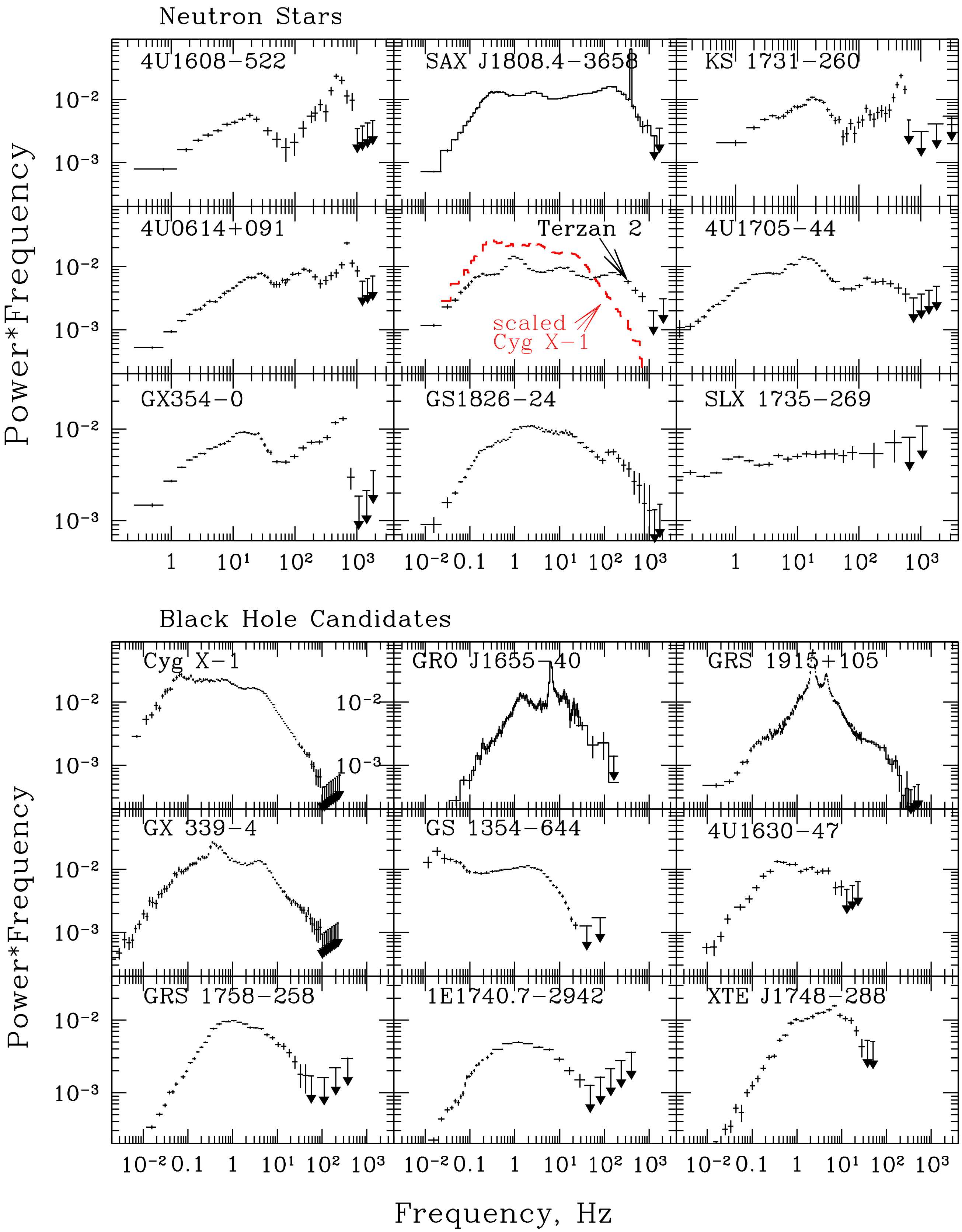

Fig. 1. Broad band power spectra of X-ray binaries in the low spectral state. Dashed line on the panel of Terzan2/1E1724-3045 shows power spectrum of Cyg X-1 scaled according to their mass ratio ($f_{\mathrm{CygX-1}} \times 7 \rightarrow f_{\mathrm{scaled\ CygX-1}}$). This scaling is not enough to delete the discrepancy in the power spectra of these sources.

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Table 1. The used observations of NS and BH binaries

Source	Proposal	Dates	Ref.
	Neutron Stars		
GX 354-0* /low state/	P10073	Feb. 22- Mar.1, 1996	
GX 354-0* /high state/	P10073	Feb.15, 1996	
4U0614+091	P30056	Mar. 13-20, 1998	1
4U1608-522 /low state/	P30062	Mar.31-Apr.2, 1998	
4U1608-522 /high state/	P30062	Mar.24-27, 1998	
SAX J1808.4–3658	P30411	Apr., 1998	2
1E1724–3045/Ter2*	P10090	Nov.5-8, 1996	3
GS 1826–24	P30054	Feb.-June 1998	
4U1705–44	P20073	Apr.1, 1997	
SLX 1735–269	P20170 P20089	Feb.- -Oct. 1997	4
KS 1731–260	P30061	2-6 Oct. 1998	5
Cyg X-2	P30418	2-6 July 1998	
	Black Holes		
Cyg X-1*	P30157	Dec.1997-Feb.1998	
GX 339-4	P20183	1997	6
GS 1354–644	P20431	Nov.19-22	7
GRS 1915+105	P20402	Feb.9, 1997	8
GRO J1655–40	P20402	Aug.14, 1997	9
4U1630-47	P30172	May-Jun.1998	10
XTE J1748–288		July 1998	11
GRS 1758-258	P10231 P10232 P20166 P30149	1996- -1998	12
1E1740.7-2942	P10231 P10232 P20166 P30149	1996- -1998	12

* – the data from these observations were also used for analysis of the radiation spectra
– [1] –Ford et al. 1997, [2] – Wijnands& van der Klis 1998, [3] – Olive et al. 1999, [4] – Wijnands& van der Klis 1999a, [5] – Muno et al. 2000, [6] – Nowak, Wilms & Dove 1999, [7] – Revnivtsev et al. 2000, [8] – Trudolyubov, Churazov& Gilfanov 1999, [9] – Remillard et al. 1999, [10] – Tomsick & Kaaret 2000, [11] – Revnivtsev, Trudolyubov & Borozdin 2000b, [12] – Main et al. 1999

fractional variability (e.g. Miyamoto et al. 1991) and the ideal Poissonian noise component ($P_{\rm Poiss}(f) = 2/R_{\rm tot}$) was subtracted from them. Then the obtained PDSs were averaged. Fractional rms normalization is very useful for our purposes because it has counting statistics noise component, with a deviation from the ideal Poisson level ($P_{\rm Poiss}(f) = 2/R_{\rm tot}$) which is fairly independent of a source count rate (see Eq. [1]). To subtract the real (not ideal) noise component due to the counting statistics from our PDSs we used the stationary Poissonian noise component level, modified by the deadtime effects described in the papers of Vikhlinin, Churazov & Gilfanov 1994, Zhang et al. 1995, Zhang et al. 1996 and successfully tested in e.g. Morgan, Greiner & Remillard 1997, Nowak et al. 1999 and Jernigan, Klein & Arons 2000.

The explicit form of the used frequency dependent counting statistics noise component, modified by deadtime effects appears as follows:

$$P_{\rm dt}(f) = \frac{2}{R_{\rm tot}} + \frac{2\xi}{R_{\rm tot}}\Bigg(\left[-2R_{\rm ph}\tau_{\rm d}\left(1-\frac{\tau_{\rm d}}{2t_{\rm b}}\right)\right] - \frac{N-1}{N}R_{\rm ph}\tau_{\rm d}\left(\frac{\tau_{\rm d}}{t_{\rm b}}\right)\cos\left(2\pi t_{\rm b} f\right) + R_{\rm ph}R_{\rm vle}\left[\frac{\sin\left(\pi\tau_{\rm vle} f\right)}{\pi f}\right]^2\Bigg), \quad (1)$$

here f – the frequency; $R_{\rm tot}$ – total (in our case – for 5 PCUs) count rate of the source in the energy band of our interest; $R_{\rm ph}$ – count rate of the source in one PCU in energy band of our interest, in our case $R_{\rm tot}\approx 5R_{\rm ph}$; $R_{\rm vle}$ – count rate of Very Large Events (VLE) in one PCU; $\tau_{\rm d}$ – deadtime value for any detected event, $\sim$9–10μs (e.g. Jahoda et al. 1996, Jahoda et al. 1997); $\tau_{\rm vle}$ – VLE preset window, 61μs (level 1) or 150μs (level 2) (see Giles 1995); $t_{\rm b}$ – time binning in our light curves ($\approx 244\mu s$); N – is the number of bins in the single light curve segment ($N = 8192$ in our case); ξ – is the dimensionless parameter (very close to 1.0) that was introduced to roughly take into account that the deadtime corrections for each PCU can be not strictly identical and the model assumption of *stationary* Poissonian process for the observed light curve is not exactly valid. But in reality ξ value is very close, within a few %, to 1.0. The closeness of ξ to 1.0 can be the indication that all used model parameters like $t_{\rm d}$ and τ_{vle} are close to the real ones.

Following the conservative approach adopted in Jernigan, Klein & Arons 2000 we fitted our PDSs at the highest frequencies ($f > 600$ Hz for NSs and $f \geq 50$ Hz for BHs) with the model for the white noise component (Eq. [1] without the first term, which was already subtracted) and the model for the source itself, leaving the deadtime model normalization parameters ξ and R_{vle} free. We used the simplest power law model for the intrinsic variability of the sources. The deduced white noise parameters ξ and R_{vle} were always consistent with the anticipated ones: $\xi \approx 1.0$ (within a few %) and $R_{vle} \sim 100-180$ cnts/s/PCU. In the cases when the R_{vle} (VLE count rate) parameter was very poorly constrained (has large statistical errors) we have it frozen at the values determined from Standard_1 mode data. This conservative approach helps us to subtract most of the PDS components that are not real components of the observed target. However, if the power spectrum of the observed source has weak and very flat noise at frequencies of 500–2000 Hz it might be treated as a noise component and will not be detected. In general, the used approach for the deadtime modeling still has some uncertainties such as the exact value of the deadtime for the photons $t_{\rm d}$, the stability of the VLE window τ_{vle} and so on. Therefore we believe that our PDSs still suffer from a small systematic uncertainty of the order of few$\times10^{-7}$ (a few percent of $P_N(f)$) in units of squared rms.

Since we were mainly interested in the high frequency continuum of the PDSs we paid special attention to all the known timing features of the PCA instrument (see e.g. PCA Group Internet Homepage http://lheawww.gsfc.nasa.gov/docs/xray/xte/pca). Apart from carefully estimating the deadtime modification of the Poissonian level in our PDSs, we ignored PCA channels 0–7 in all the analyzed data to avoid background events variability (PCA Group Internet Homepage; E. Morgan, private communication; see also Jernigan, Klein & Arons 2000) that is especially important for a weak NS sources like SLX 1735–269 and for black holes because of their low intrinsic variability at high frequencies.

To complete our power spectra with the low frequency part ($\sim 10^{-2}-1$ Hz) we used Standard_1 mode data (0.125 sec time resolution). After the above procedure the power density spectra were renormalized to units of squared relative rms *multiplied by frequency*. This helps to better visualize the distribution of the power over the Fourier frequencies (e.g. Belloni et al. 1997).

In Fig. 1 we present the power density spectra of 18 sources with subtracted frequency dependent white noise level obtained with the described procedure.

We will present below a comparison of the radiation spectra of Cyg X-1 and two NSs (Terzan2/1E1724-3045 and GX354-0). To get them we used the same RXTE data as for the timing analysis (see Table 1). The reduction of RXTE/PCA and RXTE/HEXTE data was done using standard FTOOLS 4.2 tasks and the methods recommended by RXTE Guest Observer Facility.

3. Results

In Fig. 1 (upper part of plots) we present the obtained power density spectra of nine X-ray bursters in the low/hard spectral state. For all of these sources the nature of the compact object is known – a NS with a weak magnetic field. In the lower part of Fig. 1 we present the power density spectra for nine BH candidates. For two of them (namely Cyg X-1, e.g. Gies & Bolton 1986 and GRO J1655-40, e.g. Shahbaz et al. 1999) we have the mass determinations which indicate that these sources can not be NSs. The other sources are believed to be black hole binaries based on their spectral properties.

One can see the striking similarity between the PDSs of the NS binaries and BH candidates in the low spectral state up to $\sim$10 Hz, which was already stated in the literature (see e.g. Wijnands& van der Klis 1999b, Psaltis, Belloni & van der Klis 1999, Barret et al. 2000). However, when we look at the high frequency part of the power spectra (>10–100 Hz) we notice that even in the absence of kHz quasiperiodic oscillations (QPOs) there is a dramatic difference between these two samples. The PDSs of NS binaries have significant broad noise components at the frequencies 500-1000 Hz, sometimes together with well known kHz QPOs. The power density spectra of the BH binaries in the low spectral state (the typical state for Cyg X-1) rapidly decrease at frequencies above 10 Hz and become by one–two orders of magnitude lower than those of the NSs in the same frequency band. The low frequency parts of the PDSs probably scale with the compact object mass (see e.g. Wijnands& van der Klis 1999b or Fig. 1). However, it is likely that the high frequency part of the PDSs of neutron stars demonstrates the additional noise component, see Fig. 1).

The observed empirical fact described above allows us to propose a new method for establishing the nature of the compact object in bright transient X-ray sources which appear a few times a year in the X-ray sky. We propose to classify sources whose PDS extends up to several hundred Hz without a strong decline (in coordinates "$frequency\times$ *power* vs. $frequency$") as NSs with a weak magnetic field even if the kHz QPO components are not detected in the PDS.

We understand that the sample of sources used in our analysis is not overwhelming. Moreover, the same X-ray sources in the high spectral state usually demonstrate power spectra, that may significantly differ (see Fig. 2) from each other and from the low state PDS shown in Fig.1. In other words, the NS systems in the high/soft spectral state could demonstrate the absence of significant variability at high frequencies. Therefore the absence of high frequency variability can not be the reason to state that the source is a black hole candidate. However, we propose that any source that does demonstrate significant variability (continuum or QPO) at frequencies close to 1 kHz should be considered NS. Note that for four of the nine X-ray bursters represented in Fig. 1, kHz QPOs have not yet been observed.

4. On the nature of the difference in PDS

The fate of accreting matter is very different in the case of accretion onto a BH and NS with a small magnetic field. In the case of an *accreting black hole* all the observed radiation forms in an accretion disk, its corona or in an advection flow. In the case of a *neutron star* with a weak magnetic field a significant part of the total gravitational energy should be released in the boundary layer (e.g. Shakura&Sunyaev 1988, Popham & Sunyaev 2000) or in a layer of spreading matter *on the surface of the NS* (Inogamov&Sunyaev 1999). Approximately 2/3 of the total energy releases close to the star surface in the case

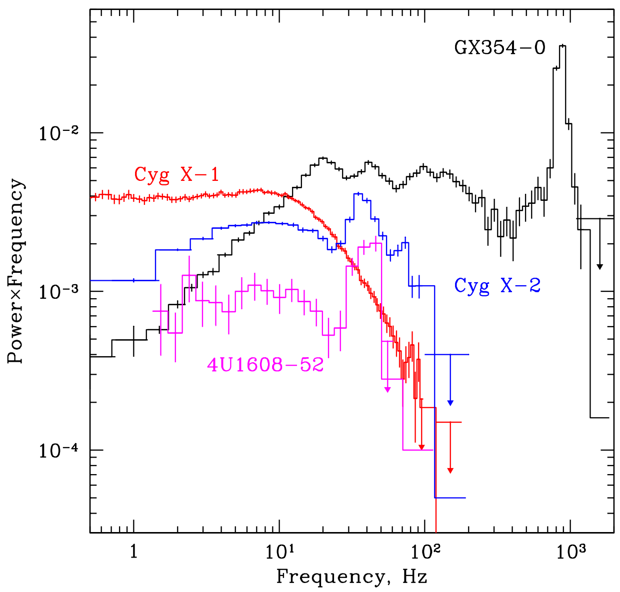

Fig. 2. Broad band power spectra of the black hole (Cyg X-1) and NS binaries (GX354-0, Cyg X-2 and 4U1608–522) in the soft/high spectral state. The difference with Fig. 1 is clearly seen for at least 4U1605–522 and Cyg X-2. GX 354-0 exhibits high frequency variability even in the soft/high state.

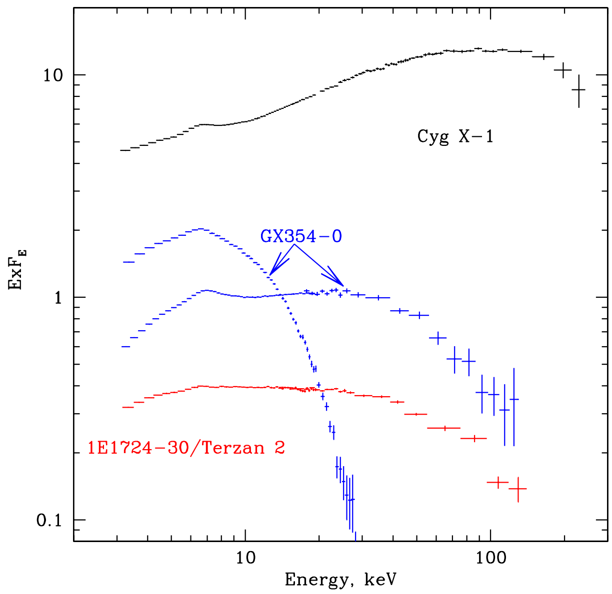

Fig. 3. The energy spectra of some of the analyzed X-ray binaries. The source GX354-0 (4U1728-34) is shown in two spectral states - low/hard and high/soft. Even in the hard state the spectra of NS are much softer than the spectrum of Cyg X-1.

of Schwarzschild geometry, see Sunyaev&Shakura 1986. Only about $\sim$1/3 of the total energy is released in the extended accretion disk. If the neutron star rotates rapidly these values change somewhat and the accretion disk contribution increases (see e.g. Sibgatullin&Sunyaev 1998). The surface of the NS is an additional source of soft photons for Comptonization. This might be the reason why the spectra of black holes in the low/hard spectral state are generally harder than the spectra of NSs (e.g. Sunyaev&Titarchuk 1989, Sunyaev et al. 1991, Churazov et al. 1997, see also Fig. 3).

4.1. The instabilities originated in the accretion disk

In the standard accretion disk, the region of the main energy release is a resonator for acoustic and other instabilities with maximal frequencies close to $\omega \sim c_s/H \sim \omega_k$, here H – the height of the accretion disk, c_s – is the speed of sound, ω_k – Keplerian frequency. In the case of accretion on the BH with slow rotation the region of the main energy release extends from $\sim 5R_g$ to $\sim 27R_g$, here $R_g = 2GM/c^2$. For the heights $H < R$ and $M_{BH} \sim 10M_\odot$ there should be a maximal frequency $f \sim 100$ Hz. Secular (Lightman & Eardley 1974) and thermal (Shakura& Sunyaev 1976) instabilities may develop in the standard accretion disk but only in the region where the radiation pressure exceeds that of matter. The characteristic time scales of these instabilities are considerably longer ($\tau \gtrsim 5/\alpha\omega_k$, where $\alpha \sim$ 0.01-1 is the viscosity parameter, see Shakura&Sunyaev 1973) than the sound oscillation time scales mentioned above. One can anticipate that the Velikhov-Chandrasekhar magnetorotational instability (Balbus & Hawley 1991) could also result in the accretion disk variations on the time scales exceeding the orbital time. An analysis of the disk turbulence (e.g. Nowak& Wagoner 1995) showed that a strong rollover above $\sim$100 Hz should present in the power spectra of an accretion disk. The phenomenological shot noise model (see e.g. Terrel 1972, Lochner, Swank & Szymkowiak 1991) and the model of coronal energy release variations (e.g. Poutanen & Fabian 1999) consider the similar absence of strong variability at frequencies higher than 100 Hz. The advection dominated accretion flow (e.g. Ichimaru 1977, Narayan & Yi 1994) are not subject to the thermal instability mentioned above. In spite of the absence of detailed studies of different instabilities for the advection flows it seems quite reasonable to assume that a limit of the order of H/c_s may be valid in this case as well. Rapid BH rotation can lead to increased frequency values, but in this case the rotation parameter a should be pretty close to the critical value 1. If $a < 0.5$ the influence of the black hole rotation is small.

All instabilities existing in the accretion disk modulate the flow of matter onto the NS surface. Therefore, we could expect that the majority of the types of variabilities we observe in accreting BHs must manifest themselves in accreting NSs with characteristic times proportional to the mass of the accreting object (see e.g. Shakura&Sunyaev 1976, Wijnands& van der Klis 1999b,

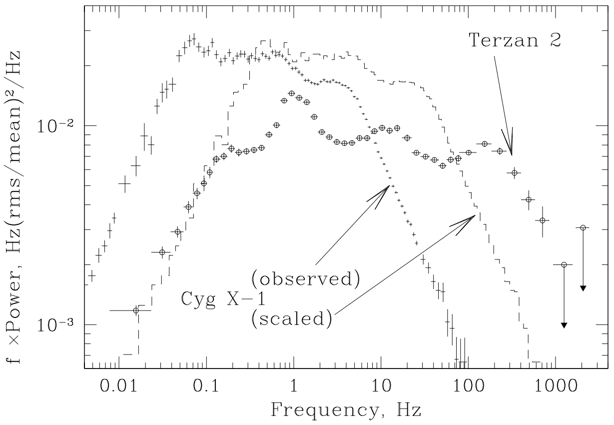

Fig. 4. The comparison of the power spectra of black hole (Cyg X-1) and neutron star (Terzan 2). The dashed line shows the power spectrum of Cyg X-1 scaled according to the mass ratio with Terzan 2 ($f_{\rm CygX-1} \times 7 \rightarrow f_{\rm scaled\ CygX-1}$). This simple scaling is important but insufficient to explain fully the difference in the high frequency variability of Terzan 2 and Cyg X-1. Note, that slopes of power density spectra of Terzan 2 and Cyg X-1 in the high and low frequency limits are similar, however the power spectrum of Terzan 2 is sufficiently broader that that of Cyg X-1.

Inogamov&Sunyaev 2000). However, in the BH systems the innermost regions of the accretion disk can generate the variability at its Keplerian frequencies (close to ∼100–200 Hz), but *their contribution to the observed PDS can be small because of the decrease of the energy release close to the last stable orbit* (e.g. Shakura&Sunyaev 1973). In the NS case, where the boundary layer can possess all accretion disk frequencies, this variability could be more pronounced.

The simplest assumption is that the characteristics frequencies in the power spectra of the sources scale as M^{-1}. This scaling law is valid for e.g. Keplerian frequency in the vicinity of the last stable orbit, thermal and secular instabilities of the accretion disk in the region of main energy release, Balbus–Hawley instability. However, this assumption is not enough to account for the observed difference in the high frequency variability of the NSs and the BHs. To demonstrate this we compared the PDS of the neutron star system Terzan2/1E1724–3045 ($M_1 \sim 1.4 M\odot$) with M_2/M_1 times scaled PDS of black hole system Cyg X-1 ($M_2 \sim 10 M_\odot$) (Fig. 1 and 4). It is obvious that such a scaling is important but insufficient to explain the high frequency variability of Terzan2. It is most likely that there is an additional component coming from the neutron star surface or boundary layer in its vicinity.

4.2. The spreading layer and the highest possible frequencies in the PDS of NSs

The inner boundaries of accretion disks around BHs and neutron stars lie at similar radii measured in the values of the gravitational radii of the central object. However, we expect a small energy release from the region with the radius smaller than the inner boundary of the accretion disk around a BH. In the case of NS accretion there is a solid surface and the matter should finally join this surface. We know this because of the existence of X-ray bursters. In accretion disks matter rotates with Keplerian velocity. The velocity of the surface of the NS is 6–3 times lower (see e.g. Strohmayer 1999 or van der Klis 2000 for reviews). Therefore matter must decelerate and release its kinetic energy in the narrow spreading layer on the surface of the NS. In the case of very low luminosities, less than 0.01 $L_{\rm crit}$ (where $L_{\rm crit}$ if the critical Eddington luminosity) all deceleration occurs in the narrow boundary layer between the innermost region of the accretion disk and the surface of the NS. We could consider this layer an atmosphere in which accreting matter is losing its kinetic energy and radiating it away (see e.g. Shakura&Sunyaev 1988). At luminosities above 0.01 $L_{\rm crit}$ the radiation pressure does not permit such a simple picture. Matter rotates around a NS and slowly spirals up the meridian toward higher latitudes. In this flow the centrifugal force and the radiation pressure force balance gravitation with very high precision. Effective gravity (the difference between the gravitational force, centrifugal force and radiation pressure force) becomes hundreds of times smaller than the gravitational force. The turbulent friction with underlying denser layers rotating with the surface velocity of the star leads to the deceleration of the flow and energy release which is radiated away. This approach predicts the existence of two broad bright belts equidistant from the star equator. These belts are fed partially with the advection of thermal energy from the regions closer to the equator (Inogamov&Sunyaev 1999). The luminosity of these bright belts exceeds the luminosity of the accretion disk.

The spreading layer may be considered a thin broad box. The flow along the latitude has Keplerian velocity in the vicinity of the equator and slowly decelerates to higher latitudes. This velocity is close to a hundred thousand kilometers per second. The sound velocity c_s within the radiation dominated box is of the order of 20 000 km/sec. The highest sound frequencies inside the box are of the order of h/c_s and might reach even 40 kHz in the case of low luminosities and 6-7 kHz in the case of luminosity close to the $L_{\rm crit}$ (Inogamov&Sunyaev 2000), here h is the thickness of the spreading layer. Simple consideration shows that we could expect a lot of turbulence generated sound, resonant sound waves and plasma instabilities with characteristic frequencies that do not end at the Keplerian frequencies, but can reach several kilohertz. The sound waves of much lower frequencies might also exist in the bright belts: one can estimate the characteristic frequencies $f \sim c_s/(2\pi R) \sim 300$ Hz for the waves propagating along the latitude and $f \sim c_s/(R\Delta\theta)$ ∼a few kHz (where $\Delta\theta$ – is the angular width of the bright belts) for the waves propagating along the meridian within the belts.

As well as we expect the Keplerian frequency on the last stable orbit ($\sim$ 200Hz for $M_{\rm BH} \sim 10 M_{\odot}$) to be the maximal possible frequency for the BH variability in X-rays, 40 kHz and 7 kHz mentioned above might be the the maximal frequencies for the NSs PDS. In both cases (for BHs and NSs) the power spectra should drop sufficiently towards these frequencies, but might be high below them.

In the spreading layer we have very strong shear in the flows along the longitude. Under such circumstances the long living whirls like those of thyphoons, Jupiter red spot or "cats eyes" due to Kelvin-Helmholtz instability might regularly appear. The evolution of the chaotic magnetic field structure inflowing into the spreading layer through the neck of the accretion disk (region with $d\Omega/dr = 0$) may produce bright spots in the spreading layer. The accretion disk screens from us half of the star, making it completely unobservable. Part of the star surface is not visible due to eclipses by the star itself at any inclination angle except i close to 0. The rotation of the bright spots leads to their regular eclipses. The duration of these eclipses is close to half of the period of the matter rotation in the spreading layer. The quasi regular eclipses (the velocity of the bright spot can slowly change) can also give rise to the additional variability (noise) of X-rays from the NS at frequencies of hundreds of Hz.

There are many different mechanisms of instabilities in the narrow (with heights from 400 m up to 1.5 km depending on the accretion rate or luminosity), thin spreading layer. Unfortunately, at the present level of sensitivity of RXTE we can not see a significant variability of the sources at the frequencies above 2–4 kHz. It is likely, that future missions with higher collecting area of the detectors can shed light on the very high frequency ($f > 5-10$ kHz) variability phenomena.

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