**ABSTRACT**

We study the time variability and spectral evolution of the black hole candidate source XTE J1650–500 using the *BeppoSAX* wide energy range (0.12–200 keV) observations performed during the 2001 X-ray outburst. The source evolves from a low/hard state (LHS) toward a high/soft state (HSS). In all states, the emergent photon spectrum is described by the sum of Comptonization and soft (disk) blackbody components. In the LHS, the Comptonization component dominates in the resulting spectrum. On the other hand, during the HSS observed by *BeppoSAX* the soft (disk) component is already dominant. In this state, the Comptonization part of the spectrum is much softer than that in the LHS (photon index $\Gamma$ is $\sim 2.4$ in the HSS vs. $\Gamma \sim 1.7$ in the LHS). In the *BeppoSAX* data, we find a strong signature of the index saturation with the mass accretion rate, which can be considered as an observational evidence of the converging flow (black hole) in XTE J1650–500. We derive power spectra (PSs) of the source time variability in different spectral states as a function of energy band. When the source undergoes a transition to softer states, the PS as a whole is shifted to higher frequencies, which can be interpreted as a contraction of the Compton cloud during hard–soft spectral evolution. It is worthwhile to emphasize a detection of a strong low-frequency red noise component in the HSS PS, which can be considered a signature of the presence of the strong extended disk in the HSS. Also as a result of our data analysis, we find a very weak sign of $K_{\alpha}$ line appearance in this *BeppoSAX* data set. This finding does not confirm previous claims by Miniutti et al. on the presence of a broad and strongly relativistic iron emission line in this particular set of *BeppoSAX* data.

**Key words:** accretion, accretion disks – black hole physics – radiation mechanisms: non-thermal – stars: individual (XTE J1650–500)

**Online-only material:** color figures

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1. **INTRODUCTION**

XTE J1650–500 was discovered by the *Rossi X-Ray Timing Explorer (RXTE)* on 2001 September 5 (Remillard 2001) and subsequently reached a peak X-ray intensity of 0.5 crab. Subsequent observations established that XTE J1650–500 is a strong black hole candidate (BHC) based on its X-ray spectrum and variability in the X-ray light curve (Markwardt et al. 2001; Revnivtsev & Sunyaev 2001; Wijnands et al. 2001; Homan et al. 2003; Kalemci et al. 2003; Rossi et al. 2004). The radio counterpart was discovered with the Australia Telescope Compact Array (ATCA) by Groot et al. (2001). Further radio observations sampled the behavior of XTE J1650–500 along all its X-ray states (Corbel et al. 2004). Orosz et al. (2004) found the period of the binary system to be $7.63 \pm 0.02$ hr, and the mass function (low limit of black hole (BH) mass) to be $2.7 \pm 0.6 M_\odot$.

We define the spectral state hardness according to the peak position in the $E(F(E))$ diagram related to X-ray spectrum $F(E)$ (in units of erg keV$^{-1}$ s$^{-1}$), where $E$ is the photon energy (see, e.g., Figure 3 in Grove et al. 1998). Following this definition, we call a low/hard state (LHS) the spectral state in which the maximum of the $E(F(E))$ diagram is located at tens of keV, while we call a high/soft state (HSS) the state where the $E(F(E))$-maximum is located at a few keV. Moreover, we call an intermediate state (IS) the state in which the source undergoes a spectral transition between the LHS and HSS. We observed XTE J1650–500 three times with *BeppoSAX* during the 2001 outburst (September 11–12, 21–23, October 3–4, see Table 1), during which the source evolves from the LHS toward the HSS. The observed outburst is a perfect case to study a source transition from the LHS to the HSS.

The long-term monitoring of Cyg X-1 has revealed not only two distinct energy spectra and transitions between them but it has also established that the corresponding time variability power spectra (PSs) evolve along with the photon spectra (see Shaposhnikov & Titarchuk > 2006, hereafter ST06; Shaposhnikov & Titarchuk 2007, hereafter ST07). Recently, the evolution of the power density spectra throughout the different X-ray states of BH X-ray binaries has also been extensively studied in many BHs by Klein-Wolt & van der Klis (2008), hereafter KVK08.

The persistence of the simultaneous PS and X-ray energy spectrum evolution suggests that the underlying physical process and conditions, which give rise to the PS, are tied to the system; and, furthermore, that this process varies in a well-defined manner as the source progresses from one spectral state to another.

Moreover, the same evolutions are seen in so many galactic X-ray binary BH sources (see e.g., a detailed discussion of these evolutions in Cyg X-1, GRO 1655–40 and GRS 1915+105 in ST07), which vary widely in both luminosity (presumably with mass accretion rate) and state. This fact suggests that the physical conditions controlling the photon spectral and the PS evolutions are similar. In particular, quasiperiodic oscillation (QPO)
frequencies are characteristics of the PS for these sources. Given that correlations between low- and high-frequency QPOs and between low-frequency QPOs and break frequencies in their PS have been found for a number of them (see Psaltis et al. 1999; Belloni et al. 2002), one can suggest that QPO phenomenon can be a universal property of all accreting compact systems.

In particular, the PS of BH binaries in hard states is dominated by a component that has a specific shape roughly described by a broken power law ($bknpl$). The low-frequency part of the $bknpl$ is mostly flat, whereas the higher-frequency part above the “break” frequency $\nu_{br}$ is a power-law $\nu^{-\alpha}$ which index $\alpha$ varies between 1 and 2. In fact, the PS of BHs are more complicated than just a $bknpl$. In the PS of BHCs, the low-frequency part (and $\nu_{br}$) increases as the source evolves from the LH state to the HS state (see e.g., TS08 and KVK08). Lyubarskii (1997) was the first to suggest a model for this time variability production in the accretion-powered X-ray sources. He considered small amplitude local fluctuations in the accretion rate at each radius, caused by small amplitude variations in the viscosity, and then studied the effect of these fluctuations on the accretion rate at the inner disc edge. His linear calculations show that if the characteristic timescale of the viscosity variations is everywhere comparable to the viscous (inflow) timescale, and if the amplitude of the variations is independent of radius, then the PS of luminosity fluctuations is a power law ($pl$) of index $\alpha = 1$, namely $\propto \nu^{-1}$. If the amplitude of the variations increases with radius, the slope of the PS of the luminosity variations $\alpha$ is steeper than 1. Lyubarskii pointed out that he had no physical model for the cause of such fluctuations. Uttley et al. (2005) pointed out that rms–flux relation is naturally explained in the framework developed by Lyubarskii.

TSA07 formulated and solved the problem of local driving perturbation diffusion in a “disklike” configuration (which can be either a geometric thin Keplerian accretion disk or a Compton cloud). The problem of the diffusive propagation of the spatially distributed high-frequency perturbations is formulated as a problem in terms of the diffusion equation for the surface density perturbations. This equation is combined with the appropriate boundary conditions. The formulation of this problem and its solution are general and classical. The emergent PS as a result of the perturbation diffusion in a given bounded configuration (either Compton cloud or Keplerian disk) has a white-red noise (WRN) shape, which can be approximated by a $bknpl$ with two indices 0 and $\alpha \gtrsim 1$, respectively. The parameters of the WRN PS are a timescale of the diffusion propagation of the local perturbations $\tau_0$ and the power-law index of the viscosity distribution over radius.

Note that the shapes of X-ray photon spectra of BH and neutron star (NS) are generic: they consist of Comptonized blackbody-like components. These Comptonization components are seen as a PL at energies higher than the BB characteristic energies. Sometimes one needs an exponential rollover in order to terminate the PL component at high energies. The main difference is that NS spectra are usually softer for the same state. Another difference in these spectra is that in the NS case there are two Comptonized blackbody (BB) components (not one as in BHC spectra) which can be related to the emission from the disk (BB color temperature about 1 keV) and NS surface (BB color temperature about 2.5 keV (see Titarchuk & Shaposhnikov 2005)).

Titarchuk et al. (1997), hereafter TMK97, introduced the generic Comptonization model (BMC model in XSPEC) which takes into account the dynamical Comptonization (converging inflow, expected in the vicinity of the central object) along with the thermal Comptonization. Note that this model can be applied to fit the observed spectra of NS and BHC sources.

In this paper, we present the results of our evolution study of the energy and power spectra in XTE J1650–500 using the BeppoSAX observations and using the aforementioned theoretical considerations of photon and PS formations. We find that this evolution is similar to that observed from Cyg X-1 (see e.g., ST06 and TSA07).

Miniutti et al. (2004, hereafter M04), reported spectral results from the same set of three BeppoSAX observations used in this sample of XTE J1650–500 during its 2001/2002 outburst. By performing the analysis in the energy range from 1.5 to 60 keV for the TOO-1 spectrum and in the range from 1.5 to 200 keV for the other two spectra, they reported the presence of a broad and strongly relativistic Fe K$_\alpha$ line with an EW of about 200 eV, depending on Target of Opportunity Observation (TOO). We re-analyze the same BeppoSAX data set adopting the entire BeppoSAX energy range (0.12–200 keV) in order to check the presence of a strong K$_\alpha$ line in the data. We find a very weak sign of K$_\alpha$ line appearance.

Results of our detailed spectral analysis are the subject of our next paper (E. Montanari et al. 2009, in preparation). Here, we present results on the simultaneous evolution of the spectral and temporal properties and compare them with that in other BH sources (see ST06 and ST07).

Our approach is twofold: on the one hand, we try to fit all photon and power spectra with the same generic simple model, in order to compare them directly. On the other hand, we study the source in the framework of a physical model in the attempt to find a self-consistent scenario that can help us to understand the physics of the spectral and timing evolution that we observe.

In Section 2, we briefly describe the BeppoSAX data from XTE J1650–500. Details of our spectral fitting are presented in Section 3. We discuss an observational evidence of a converging flow in Section 3.1. We present the results of our analysis of K$_\alpha$ appearance in the data in Section 3.2. Description of XTE J1650–500 PS and QPO identification are presented in Section 4, where we also discuss a correlation of PS versus spectral state (photon index) revealed in XTE J1650–500. Discussion and conclusions follow in Section 5.

### Table 1

| Obs. | Start Time (UT) | End Time (UT) | LECS (ks) | MECS (ks) | HPGSPC (ks) | PDS (ks) |
|------|----------------|---------------|----------|-----------|-------------|---------|
| 1    | 2001 Sep 11 10:57:04 | 2001 Sep 12 18:43:06 | 20.3     | 47.4      | 47.0        | 22.2    |
| 2    | 2001 Sep 21 18:15:39 | 2001 Sep 23 14:05:40 | 15.9     | 63.9      | 73.3        | 30.3    |
| 3    | 2001 Oct 03 16:36:53  | 2001 Oct 04 10:15:56  | 7.2      | 27.8      | 33.0        | 12.8    |
2. OBSERVATIONS AND DATA REDUCTION

XTE J1650–500 was observed on September 2001 11–12, 21–23 and October 3–4 during three TOOs by the Narrow Field Instruments (NFIs) on board BeppoSAX (Boella et al. 1997a). Table 1 reports the observation log along with the on-source exposure times. The NFIs include a Low Energy Concentrator Spectrometer (LECS, 0.1–10 keV; Parmar et al. 1997), three Medium Energy Concentrator Spectrometer (MECS, 1.5–10 keV; Boella et al. 1997b), a High-Pressure Gas Scintillation Proportional Counter (HPGSPC, 4–120 keV; Manzo et al. 1997), and a Phoswich Detection System (PDS, 15–200 keV; Frontera et al. 1997). The SAXDAS data analysis package is used for processing data.

For each instrument, we perform the spectral and temporal analysis in the energy range in which the response function is well determined; given the high statistics of the source the energy range is 0.12–4.0 keV for the LECS, 2.5–10 keV for the MECS, 8–30 keV for the HPGSPC, and 15–200 keV for PDS. Note that, at the given high-count rate, the available LECS response function is not reliable, therefore the SAX/LECS Matrix Generation Program “lemat” is used to obtain the appropriate response function of the instrument. MECS unit 1 was not operative. Spectra from MECS units 2 and 3 are merged. The spectra so obtained are rebinned taking into account the energy resolution of the instruments in order to get independent data points.

Previously, M04 analyzed the same set of BeppoSAX data integrating the source spectra over the entire duration of each of the three observations. However, this integration time could provide distorted spectra, given that the high statistics of the source the energy range is 0.12–4.0 keV for the LECS, 2.5–10 keV for the MECS, 8–30 keV for the HPGSPC, and 15–200 keV for PDS. Note that, at the given high-count rate, the available LECS response function is not reliable, therefore the SAX/LECS Matrix Generation Program “lemat” is used to obtain the appropriate response function of the instrument. MECS unit 1 was not operative. Spectra from MECS units 2 and 3 are merged. The spectra so obtained are rebinned taking into account the energy resolution of the instruments in order to get independent data points.

For the temporal analysis, we use standard fast Fourier techniques. Source PSs are normalized to rms units using subtraction of the Poissonian noise level. Dead time corrections have been taken into account according to van der Klis (1989). The binning time for the analysis is a few ms. PSs are calculated using data stretches of ∼ 100 s and then averaged. In this way, we obtain the reliable PSs in a frequency range from 0.01 to 100 Hz. Unfortunately, we cannot provide much longer time stretches to extend the frequency passband to lower values due to frequent interruptions in the data rate. We present only data points that are statistically significant (see Section 4 for more details).

The uncertainties of the model parameters are given at 90% confidence level, whereas those shown in all figures are 1σ errors.

Namely, in the TOO-1 the spectra were divided in 12 time intervals and numerated from I101 to I112, in the TOO-2 they were divided in 19 intervals (from I201 to I219), whereas in the TOO-3 they were divided in eight intervals (from I301 to I308). Note that LECS data are not available for five intervals of TOO-2.

In Figure 1, we display the source light curve related to the period from 2001 September 11 to October 4, for the 2–3 keV and 20–60 keV energy bands. The integration time of each bin is that of the IDs intervals used for spectral analysis. In Figure 1, one can clearly see an overall anti-correlation between the two light curves related to these two energy bands during TOO-1 and TOO-2. Note that the transition to a softer spectrum becomes prominent in TOO-2 and continues during TOO-3 observations. For TOO-2 (see Figure 1), a variable rate is evident at low energies, unlike an almost stable count rate at high energies. This different time behavior at different energies can also be seen from Figure 2 where we compare the energy behavior of MECS mean count rates in the time intervals I202 and I207.

We model the energy spectra using XSPEC 11.2.0 software package (Arnaud 1996). A systematic error of 1% is added in order to take into account unavoidable uncertainties in the response functions. In the multi-instrument fits, we leave free to vary the relative normalization of LECS, HPGSPC, and PDS with respect to MECS and the derived unfolded spectra are renormalized to the MECS level for a clarity of display.

For the temporal analysis, we use standard fast Fourier techniques. Source PSs are normalized to rms units using subtraction of the Poissonian noise level. Dead time corrections have been taken into account according to van der Klis (1989). The binning time for the analysis is a few ms. PSs are calculated using data stretches of ∼ 100 s and then averaged. In this way, we obtain the reliable PSs in a frequency range from 0.01 to 100 Hz. Unfortunately, we cannot provide much longer time stretches to extend the frequency passband to lower values due to frequent interruptions in the data rate. We present only data points that are statistically significant (see Section 4 for more details).

The uncertainties of the model parameters are given at 90% confidence level, whereas those shown in all figures are 1σ errors.
3. X-RAY ENERGY CONTINUUM SPECTRA

In our analysis, all derived spectra (39) cover the 0.12–200 keV energy band, except five intervals in which the LECS data are not available. In this case, the energy band was from 2.5 to 200 keV.

To describe the continuum spectrum, we use the bulk motion Comptonization model (BMC in XSPEC; Titarchuk et al. 1997), which is a generic Comptonization model. This model can be used if the photon energy is less than the mean electron energy of the Compton cloud \( E_{\text{av}} \). The choice of this particular theoretical model is provided by the robust nature of the BMC model for different spectral states and independence of the specific type of Comptonization scenario involved. The BMC model spectrum is the sum of a BB component (which is the disk radiation directly seen by the observer) and the fraction of a BB component Comptonized in the corona.

The model has four parameters: the color temperature \( kT_{\text{bb}} \) of a thermal photon spectrum (BB), the energy spectral index \( \alpha = \Gamma - 1 \), where \( \Gamma \) is the pl. photon index, the parameter \( A \), which is related to the weight \( [A/(1+A)] \) of the Comptonization component, and the normalization of the BB component \( C_{\text{bb}} \). The BMC model is valid for the general case of Comptonization when both bulk and thermal motion are included.

For the thermal Comptonization, \( E_{\text{av}} \) is related to electron temperature \( kT_{\text{av}} \sim 2kT_{\text{e}} \). When the bulk motion Comptonization is dominant, \( E_{\text{av}} \) is related to the bulk kinetic energy of the electrons \( E_{\text{av}} \lesssim m_e c^2 \). In the thermal Comptonization case, for energies less than \( E_{\text{av}} \), COMPTT and BMC models are very similar. The thermal Comptonization and the dynamical (bulk motion) Comptonization are presumably responsible for the spectral formation in the hard state and the soft state, respectively. Therefore, one needs a general model such as the BMC that describes the spectral shape regardless of the specific type of Comptonization. Although the thermal Comptonization model can properly fit the spectral shape of the observed spectra for all spectral states, it would give physically unreasonable values of the best-fit parameters for the soft state spectra. Notably, Wilms et al. (2006) found optical depth \( \tau \) of the Compton cloud inferred from the COMPTT model that significantly decreases toward the HSS. It is very difficult (in the framework of any reasonable physical model) to justify this tendency of \( \tau \) to decrease when the mass accretion rate increases during the hard-to-soft state transition (see e.g., ST06). However, the spectral index \( \alpha \) inferred using the best-fit COMPTT parameters \( \tau \) and \( kT_{\text{e}} \) is a physical characteristic of the Comptonization process. In fact, the spectral index \( \alpha \) is the reciprocal of the Comptonization parameter \( Y \) (see e.g., Bradshaw et al. 2007) and it is independent of any type and model of Comptonization (thermal or bulk).

It is important to emphasize the principal difference and similarity in using BB-like spectra (BBODY in XSPEC) and multicolor disk spectra (disk BB in XSPEC) as soft photon spectra. In fact, Borozdin et al. (1999), hereafter BRT99, demonstrated that in a limited energy range (e.g., RXTE/PCA) the diskBB is fit by a BB spectrum. The color BB temperature is the best-fit parameter, which is related to the effective radius of the emission area of the disk. It is evident that the best-fit values of the color temperature and effective radius depend on the energy range of the instrument (see BRT99). Any disk model requires the integral of the local spectra over radius.

These local emergent spectra are not necessarily BB-like spectra and they are indeed formed as a result of the radiative transfer effects, which depend on the assumption of the local density and temperature structure. Moreover, the specific disk BB model assumes a temperature distribution with the disk radius that is likely not the real distribution. Thus, taking all that into account, we have preferred to describe the thermal (BB-like) component of the source spectrum by adding another BB to that already included in the BMC model.

Following XSPEC notation, the model used to describe our spectra is given by \( F(E) = \text{WABS} \times (\text{BBODY} + \text{BMC}) \times \text{SMEDGE} \times \text{HIGHECUT} \). Here WABS is the XSPEC photoelectric absorption model, which takes into account a possible intrinsic photoelectric absorption in the source and/or external absorption of X-ray source emission in the way toward the Earth. The BMC Comptonization model describes both direct (from an innermost part of the disk) and Comptonized photons (from the corona), the added BBODY component describes the direct soft photons belonging to the disk part at a greater distance from the central object, which spectrum can be only slightly affected by upscattering in the corona. The SMEDGE (smeared K-edge) model represents a possible interaction of the photons originated in the inner part of the X-ray source with a wind (see Laurent & Titarchuk 2007). The HIGHECUT (high-energy cutoff) model enables to take into account the curvature effect of the Comptonized photon spectrum at high energies (that is above 100 keV in the LHS spectra) due to the recoil effect which is neglected by BMC. HIGHECUT is found to be needed to describe the LHS energy spectrum, whereas, for the HSS, no high-energy cutoff is needed.

Most of the 39 spectra are found to be very well fitted by the assumed input model. Only for nine spectra, the model has a null hypothesis probability less than 0.05, with three of them with null hypothesis probability less than 0.01, the smallest value being \( 3.7 \times 10^{-3} \).

The best-fit parameters of six typical spectra extracted from the entire set are shown in Table 2. As can be seen, the temperature \( kT_{\text{bb}} \) of the soft BB varies from 0.18 to 0.36 keV, whereas that of the BMC, \( kT_{\text{bb}} \), varies in the range from 0.39 to 0.56 keV, depending on the spectral state. For the same time intervals of Table 2, we show in Figure 3 the best-fit \( E F(E) \) spectra in keV cm\(^{-2}\) s\(^{-1}\) units. In the LHS spectra I105 and I111, the relevant Comptonization contribution is related to the thermal Comptonization of soft (disk) photons off hot electrons of Compton cloud (corona). Instead, in the HSS spectra (see spectra I215, I216, I130, and I306 in Figure 3), the BB emission (both BBs), presumably related to the intrinsic disk spectrum, is dominant in the resulting spectrum, whereas the hard (steep pl.) photons, probably formed in the relatively cold (a few keV temperature) compact region, are only a small fraction of the total flux.

As we noted above, the use of the thermal Comptonization model (COMPTT) is physically justified for the fitting of the LHS spectra only. For comparison with the results reported in Table 2, for time intervals I105 and I111 we implemented a fit using a model \( \text{WABS} \times (\text{BB} + \text{COMPTT}) \times \text{SMEDGE} \) (see Table 3). In fact, the fit quality obtained using the COMPTT model is not so good as that in the case of BMC (compare the \( \chi^2/(\text{do}f) \) values in Tables 2 and 3) presumably because a modest converging flow contribution to the overall Compton upscattering is already present in TOO-1. In general, the worse quality fits introduce additional systematic errors in the best-fit model parameters. In particular, the photon index, obtained

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\(^2\)COMPTT model was introduced by Titarchuk (1994), Titarchuk & Lyubarskij (1995), and Hua & Titarchuk (1995) to describe the spectrum of thermal Comptonization in the whole energy range.
Table 2
Parameters of the Model: WABS × (BBODY + BMC) × SMEDGE × HIGHECUT

| Model | Parameters | I105 | I111 | I215 | I216 | I303 | I308 |
|-------|------------|------|------|------|------|------|------|
| WABS  | $N_{	ext{H}}$ (10$^{22}$ cm$^{-2}$) | 0.62$^{+0.07}_{-0.07}$ | 0.62$^{+0.08}_{-0.07}$ | 0.48$^{+0.02}_{-0.02}$ | 0.49$^{+0.02}_{-0.02}$ | 0.50$^{+0.03}_{-0.03}$ | 0.52$^{+0.02}_{-0.02}$ |
|       | $kT_{	ext{ab}}$ (keV) | 0.19$^{+0.02}_{-0.02}$ | 0.19$^{+0.02}_{-0.02}$ | 0.36$^{+0.03}_{-0.03}$ | 0.35$^{+0.02}_{-0.02}$ | 0.34$^{+0.03}_{-0.03}$ | 0.33$^{+0.02}_{-0.02}$ |
| BMC   | $\Gamma$ | 1.74$^{+0.01}_{-0.01}$ | 1.81$^{+0.02}_{-0.02}$ | 2.50$^{+0.02}_{-0.02}$ | 2.38$^{+0.03}_{-0.03}$ | 2.32$^{+0.04}_{-0.04}$ | 2.34$^{+0.04}_{-0.04}$ |
|       | $kT_{b}$ (keV) | 0.40$^{+0.02}_{-0.02}$ | 0.39$^{+0.02}_{-0.02}$ | 0.56$^{+0.04}_{-0.04}$ | 0.55$^{+0.04}_{-0.04}$ | 0.52$^{+0.04}_{-0.04}$ | 0.54$^{+0.04}_{-0.04}$ |
|       | $\log A$ | 0.20$^{+0.06}_{-0.06}$ | 0.20$^{+0.06}_{-0.06}$ | $-0.31^{+0.07}_{-0.07}$ | $-0.31^{+0.07}_{-0.07}$ | $-0.44^{+0.07}_{-0.07}$ | $-0.46^{+0.07}_{-0.07}$ |
|       | $N_{\text{hb}}/N_{\text{bb}}$ | 0.8$^{+0.4}_{-0.5}$ | 0.9$^{+0.3}_{-0.4}$ | 1.4$^{+0.9}_{-0.9}$ | 1.3$^{+0.9}_{-0.9}$ | 1.1$^{+0.8}_{-0.8}$ | 1.3$^{+0.8}_{-0.8}$ |
| SMEDGE| $\tau_{\text{max}}$ | 2.04$^{+0.10}_{-0.13}$ | 1.96$^{+0.17}_{-0.17}$ | 3.5$^{+0.2}_{-0.2}$ | 3.6$^{+0.3}_{-0.3}$ | $5.3^{+0.9}_{-1.0}$ | $4.5^{+0.6}_{-0.6}$ |
| HIGHECUT | $E_{p}$ (keV) | 114$^{+5}_{-6}$ | 114$^{+5}_{-6}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ |
|       | $\chi^{2}/$dof | 179.0/164 | 167.7/163 | 177.6/151 | 194.9/153 | 164.6/131 | 190.7/148 |

Note. a HIGHECUT was used only for the LHS. Parameters not listed in the table were held fixed. For HIGHECUT: $E_{\text{cut}} = 10$ keV; for SMEDGE: $E_{\text{edge}} = 7.1$ keV, index for photoelectric absorption = 2.67 (default value), smoothing width = 10 keV. Errors are given at the 90% confidence level.

Figure 3. Evolution of the $EF(E)$ energy spectra with time. The LHS spectra (I105 and I111) show the key role of the thermal Comptonization of soft (disk) photons in the extended hot Compton cloud (corona), while the HSS spectra (I215–I216, I303, and I308) show that prominent contribution of the soft BB-like component due to the direct emission from the disk. In this case the hard X-ray component (i.e., the steep pl.) is formed in the relatively cold (temperature of a few keV) compact region which is presumably a converging flow into the BH.

(A color version of this figure is available in the online journal.)

using COMPTT best-fit optical depth $\tau$ and electron temperature $kT_e$ and using the formula for the index related to $\tau$ and $kT_e$ (see Titarchuk & Lyubarskij 1995), is 0.4 higher than that inferred using BMC.

In Sections 4 and 5, we present the arguments for the compactness of the steep pl. emission region, which is presumably a CF streaming toward the innermost part of the BH.

3.1. Observational Evidence of the Converging Flow (Black Hole) in XTE J1650–500

It is important to emphasize once again (see above) that the spectral index $\alpha$ (i.e., $\Gamma-1$) is the reciprocal of the Comptonization parameter $\Gamma$ (see e.g., Bradshaw et al. 2007) and it is independent of the Comptonization model (thermal or bulk). The parameter $Y = N_{\text{sc}}\eta$ is the mean number of scatterings $N_{\text{sc}}$ times the average fractional energy change per scattering $\eta$. The number of scatterings of Comptonized (upscattered) photons in the converging flow $N_{\text{sc}}$ is proportional to the optical depth $\tau$, given that in the converging flow the photons can be only effectively upscattered in the direction of the bulk motion, and thus $N_{\text{sc}} \propto R/l = \tau$, where $R$ is the converging flow characteristic radius and $l$ is the photon free path. It is also worth noting that, in the converging flow, $\tau$ is also equal to the dimensionless mass accretion rate $\dot{m} = M/M_{\text{Edd}}$ where $M_{\text{Edd}}$ is defined as $M_{\text{Edd}} = L_{\text{Ed}}/c^2$ (see Titarchuk et al. 1997 for more details). On the other hand, the change of the converging flow fractional energy per scattering $\eta$ is inversely proportional to $\tau$ ($\eta \propto 1/\tau$) when $\tau \gg 1$ (see Laurent & Titarchuk 2007 for more details).

Consequently, $Y = N_{\text{sc}}\eta$ and thus $\Gamma = 1/Y + 1$ saturate to a constant value when $\tau$ (or $\dot{m}$) increases. Observationally, this index saturation can be revealed if one can find a correlation between $\Gamma$ and BMC normalization $C_{N} = L_{39}/d_{10}^{2}$, where $L_{39} = L_{d}/(10^{39}$ erg s$^{-1}$) is the luminosity of the seed photon source (disk) in units of 10$^{39}$ erg s$^{-1}$ and $d_{10}$ is the distance to source in units of 10 kpc. This correlation of the index $\Gamma$ with $C_{N} = L_{39}/d_{10}^{2}$ implies the correlation of $\Gamma$ versus $m$ given that $L_{d}$ as a disk luminosity is proportional to $m$, namely $L_{d} \propto \varepsilon_{\text{eff}}\eta m$, where $m = M/M_{\text{Edd}}$ is the BH mass in units of solar mass and $\varepsilon_{\text{eff}}$ is the efficiency of the gravitational energy release in the accretion disk (see e.g., Shakura & Sunyaev 1973). In principle, the efficiency $\varepsilon_{\text{eff}}$ can depend on the inner radius of the disk $R_{\text{in,d}}$, that is, indirectly depends on $m$. However,

Table 3
Parameters of the Model: WABS × (BBODY + COMPTT) × SMEDGE

| Interval | I105 | I111 |
|----------|------|------|
| $N_{\text{H}}$ (10$^{22}$ cm$^{-2}$) | 0.38$^{+0.02}_{-0.03}$ | 0.39$^{+0.03}_{-0.02}$ |
| $kT_{\text{ab}}$ (keV) | 0.30$^{+0.01}_{-0.01}$ | 0.31$^{+0.01}_{-0.01}$ |
| $T0$ (keV) | 0.45$^{+0.03}_{-0.04}$ | 0.46$^{+0.03}_{-0.04}$ |
| $\tau$ | 1.33$^{+0.06}_{-0.08}$ | 1.20$^{+0.11}_{-0.16}$ |
| $kT_{b}$ (keV) | 31$^{+1}_{-1}$ | 32$^{+1}_{-1}$ |
| $\Gamma$ | 2.15$^{+0.03}_{-0.03}$ | 2.12$^{+0.06}_{-0.06}$ |
| $N_{\text{hb}}/N_{\text{compt}}$ | 0.52$^{+0.02}_{-0.01}$ | 0.68$^{+0.02}_{-0.01}$ |
| SMEDGE-$\tau_{\text{max}}$ | 1.74$^{+0.08}_{-0.12}$ | 1.7$^{+0.2}_{-0.2}$ |
| $\chi^{2}/$dof | 237.0/165 | 210.4/164 |

Note. a Errors are given at the 90% confidence level.
Figure 4. Photon index evolution as a function of BMC normalization $L_{90}/d_{10}^2$ (which is proportional to mass accretion rate in the disk). Colors correspond to TOO-1 (black), TOO-2 (red), TOO-3 (green).

(A color version of this figure is available in the online journal.)

In HSS, $R_{in,d}$ presumably reaches its lowest limit of about $3R_S$ (see e.g., Shrader & Titarchuk 1999) and thus, in HSS, the index versus $C_N$ correlation is equivalent to the correlation between index and $m$. This implies that in HSS the index saturation with $C_N$ is equivalent to the index saturation with $m$.

In Figure 4 we present an observational evidence of the index saturation with $L_{90}/d_{10}^2$, and thus with $m$, which can be considered as an observational signature of a converging flow (BH) in XTE J1650–500.

3.2. On Iron Fluorescence Line Determination

Limiting our considerations to the BeppoSAX TOO we confirm the broad excess at $\sim 6.4$ keV found by M04 in all of the three observations if we adopt, as MO4 did, the XSPEC reflection model PEXRIV. However, the excess is present only in the first TOO if we use a two-phase accretion disk corona model which also includes the reflection effect (XSPEC COMPPS model; E. Montanari et al. 2009, in preparation). It is worth noting that when we use COMPPS model we find a strange effect (unexpected in the scenario described by this model) that the iron line (thought to be due to reflection from the disk) is present when the reflection parameter is low (in TOO-1) and it is completely absent when the reflection parameter becomes larger (in TOO-2 and TOO-3; see Montanari et al. 2004). Also as we have already mentioned above, in the framework of the COMPPS model there is a puzzling effect of significant decrease of the optical depth of the Compton cloud when the source evolves to the HSS (Montanari et al. 2004).

On the other hand, using the input continuum model described in Section 3 and the entire BeppoSAX spectral energy range we find a very marginal evidence for the presence of the Fe fluorescence line in the data. We illustrate our findings in Figure 5.

Adopting the 0.12–200 keV energy range, the fit of the continuum model $WABS \times (BB+BMC) \times SMEDGE \times HIGHCUT$ to the spectrum I108, used as an example, is shown in panel 2 (starting from the top). As can be seen, the above continuum model gives a very satisfactory description of the data ($\chi^2/\text{dof} = 150/164$), with no need of adding a Fe $K\alpha$ line model. Instead the SMEDGE model appears crucial for a good fit. The fit of the above continuum model with no SMEDGE to the same spectrum (see the top panel) is highly unacceptable ($\chi^2/\text{dof} = 430/165$). The apparent sinusoidal pattern of the residuals to the model is a clear sign of the bad fit quality.

Note the addition of a $K\alpha$ line ($\text{Laor}$ model) to the continuum model with no SMEDGE gives an unacceptable fit ($\chi^2/\text{dof} = 300/163$, see panel 3), but it becomes acceptable ($\chi^2/\text{dof} = 136/109$, see panel 5), if we limit the spectrum energy bandwidth to 1.5–60 keV (the band used by M04). However the model which is valid in 1.5–60 keV is not valid in the entire BeppoSAX energy band. Namely, the model $WABS \times (BB+BMC+\text{Laor}) \times HIGHCUT$, with the best-fit parameter values found for the 1.5–60 keV energy band, does not fit the data related to the entire BeppoSAX energy range from 0.12 to 200 keV ($\chi^2/\text{dof} = 1315/164$, see panel 6).

We have also attempted to understand why M04, using the SMEDGE model as we do, obtained different results. Limiting the analysis to the spectrum I108, assumed as an example, we actually find that freezing the energy of the edge to the best-fit value reported by M04 ($E_{\text{edge}} = 8.3$ keV being consistent with a very high ionization state of iron (ion XXII), see Kallman et al. 2004) gives the presence of a significant emission line. The line disappears when $E_{\text{edge}}$ is left free to vary, finding, as a best-fit value, 7.2 keV.

To conclude, iron $K\alpha$ line appearance strongly depends on the energy band used to describe the continuum emission. With our best-fit continuum model, that gives the best description of the source spectrum in the entire 0.1–200 keV BeppoSAX energy band, the line is not required.

Although no significant emission line is evident in the data, adding the XSPEC $\text{Laor}$ model to our best-fit model (see Section 3) slightly improves the fits ($\Delta \chi < 10$ with a
decrease of 4 dof for about 160 initial dof) for some observation intervals belonging to TOO-1 (LHS). The resulting line, of equivalent width ranging from few tens eV to about 100 eV, is almost symmetric with its center being situated in the energy range between 5 and 5.5 keV. For all of other intervals the normalization of the line goes to zero.

Concerning the SMEDGE model used in the best-fit description of our spectra, it is worth noting there is a relation between Thompson optical depth $\alpha$ and $K$-line formation is indeed strongly related to edge formation (see e.g., Basko et al. 1974; Basko 1978; Kallman et al. 2004; Laming & Titarchuk 2004; Laurent & Titarchuk 2007). However, it is not always true that the detection of the K-edge in the data implies the $K_\alpha$-line detection. The physics of the K-edge and $K_\alpha$ formation is the following: photons of energies higher than 7.1 keV ionize the iron K-shell and this ionization effect leads to emission of $K_\alpha$-photon (iron $K_\alpha$-fluorescence) with a probability of $\omega_K \lesssim 0.3$ (where $\omega_K$ is K-yield), whereas with probability $(1 - \omega_K)$ the $K_\alpha$ energy goes to an ionized electron. So the edge can always be there but the $K_\alpha$-photon is emitted with a probability less than 0.3 and in addition this probability is affected by the electron density of the surrounding medium (see more details in the aforementioned references on this subject). Even if the $K_\alpha$-photon is emitted it does not mean that this photon can be detected and seen by the Earth observer. These photons can be absorbed when they propagate through the medium (e.g., in the wind) and they can also be scattered off electrons and significantly change their energy, that is, washed out from the resulting spectrum. All these effects of line appearance and disappearance have been reproduced in simulations by Laming & Titarchuk (2004) and Laurent & Titarchuk (2007).

4. POWER SPECTRUM AND TIMING-SPECTRAL CORRELATION

We succeeded to derive accurate PSs of the source time variability thanks to the high-source brightness during outburst. In particular, during TOO-1, when the source was mainly in the LHS, it was possible to obtain the PS in several energy intervals within the broad 0.1–200 keV BeppoSAX operational band.

4.1. Phenomenological (Lorentzian) Model

First we made the analysis of the PS using, as an input model, the superposition of Lorentzian functions (Lorentzian model). We compared their characteristics with those identified by KVK08 for a number of BHs. A Lorentzian function is given by

$$L(v) = K \frac{\hat{\nu}/2\pi}{(v - \nu_0)^2 + (\hat{\Gamma}/2)^2}, \quad (2)$$

where $\nu_0$ is the centroid frequency and $\hat{\Gamma}$ is the full width at half-maximum (FWHM) of the function.

We used broad Lorentzians to fit the continuum spectrum and narrow Lorentzians to fit QPO features. In Figure 6 (bottom panel), we illustrated the fitting results and the characteristics of the PS components in terms of frequency $\times$ power diagram. Note the PS unit is $(\text{rms}/\text{mean})^2 \text{Hz}^{-1}$ and thus the frequency $\times$ power unit is $(\text{rms}/\text{mean})^2$. Below we presented a comparison of these characteristics with those found by KVK08.

The continuum of all derived LHS PSs is found to be well described by the sum of two broad Lorentzians $L_1$ and $L_2$. Following the KVK08 notation, we formally call them $L_0$, $L_3$, respectively. We report the best-fit characteristic frequency of these broad Lorentzians in Table 4. This frequency corresponds to the maximum of the $vL(v)$ diagram $\nu_{\text{max}} = [\nu_0^2 + (\hat{\Gamma}/2)^2]^{0.5}$. The presented PSs are results of integration over the entire duration of each TOO.

Using Figure 6 and Table 4 one can see that, in addition to the two broad Lorentzians $L_0$ and $L_3$, the 2–10 keV power–frequency diagram of the LHS (TOO-1) requires two narrow Lorentzians: a low-frequency (LF) QPO and a higher-frequency QPO at $\nu_{\text{QPO1}} \sim 1.5$ Hz and $\nu_{\text{QPO2}} \sim 3$ Hz, respectively. These two QPOs were introduced by KVK08 as LF and LF$^*$, respectively. Note that $\nu_{\text{QPO2}} \sim 3$ Hz (or LF$^*$) was found to be consistent with the second harmonics of $\nu_{\text{QPO1}}$ (or LF).

However, in the 0.1–2 keV energy channel, no evidence of $\nu_{\text{QPO2}}$ is found and the characteristic frequency of the broad Lorentzian $L_0$, which describes the hump to the right of the QPO frequency (see the blue line in the right-bottom panel of Figure 6), is at 23 Hz. Note the $L_0$-hump is located at $\sim 2$ Hz in the 2–10 keV power–frequency diagram.

In Table 5, we show the energy dependence of the LHS PS components in the broad energy bands from 0.1–2 keV to 15–200 keV. The characteristic frequencies of $L_0$ are consistent with each other up to 15 keV and the $L_0$ characteristic frequencies are consistent with each other in the 2–4, 4–10 and 8–15 keV energy intervals. Using the $L_0$–$L_0$ relation found (for the energy band 2–25 keV) by Wijnands & van der Klis (1999), updated in KVK08, we find that our medium energy data points are consistent with that relation. Also the PS narrow components $L_{\text{QPO1}}$ and $L_{\text{QPO2}}$ clearly detected in the 4–10 keV and 8–15 keV bands satisfy the Wijnands and van der Klis $L_{\text{LF}}$–$L_0$ relation (see Figure 10 in KVK08).

It is worth noting that, in the 0.1–2 keV and 15–200 keV energy intervals, the $L_0$ frequencies are an order of magnitude higher than those at medium energies. In fact, it is the first time that the high values of $\nu_{\text{max}}$ ($\sim 23$ Hz, $\sim 50$ Hz in the 0.1–2 keV and 15–200 keV energy bands, respectively) are discovered from this source. Their identification with the $L_0$ introduced by, for example, KVK08 is not obvious. Unfortunately, there are no data in the literature to statistically study a
possible correlation between \( L_b \) and \( L_h \) at these energies, unlike what can be done at medium energies with RXTE data (see e.g., KVK08). The \( L_b \) components in the 0.1–2 keV and 15–200 keV energy bands can be related to PS physical components, which are different from that in the medium energy bands (see details of the physical interpretation in Section 4.2).

In the HSS, the PS continuum is still found to be well described by the sum of two broad Lorentzians, but in this case (see Table 4 and Figure 6), \( L_h \) is no more visible, while a very low frequency noise (VLFN) emerges. It is important to emphasize that the characteristic frequency of \( L_b \) increases from the LHS to the HSS. Our finding is in agreement with the fact that the \( L_b \) characteristic frequency is shifted to higher values during the source evolution from the LHS to the HSS (see also Figure 4 in KVK08). We also confirm the KVK08 result that LVFN component occurs in the HSS, but is absent in LHS (compare our Figure 6 (bottom panels) with panels (a) and (e) in Figure 4 of KVK08).

Furthermore, we find that the \( Q \)-value, defined as \( Q = \nu_0 / \tilde{\Gamma} \), is in the range of 0–0.5 for \( L_b \), \( L_h \) components and that is in the range of 4–6 for PS narrow components \( L_{QPO} \). As one can see from Figure 6 that rms/mean values are 10% and 30% for \( L_b \) and \( L_h \) of the LHS PS components, respectively, in 0.1–2 keV. The corresponding rms/mean values for the LHS \( L_b \) and \( L_h \) in 2–10 keV band are about 10% (see the left-bottom panel of Figure 6). However, the variability power of the PS components drastically decreases in the HSS, and their rms values are less than 1%. It is worth noting that these ranges of \( Q \) and rms values are consistent with that found by KVK08 (see Table 1 there).

4.2. Physical (Diffusion) Model

The analysis of the PS was performed using a simplified version of the diffusion model (see TSA07 and TS08) in which the PS continuum shape at frequencies below the driving frequency can be approximated by a \( bknpl \). The results of the model fitting to the data are shown in Tables 6–8. We also present the model fitting results in Figures 6 and 7.

In particular, in Figure 7 and Table 6 we show the energy dependence of the LHS PS and the variability power that decreases with energy (mainly above 10 keV), while it preserves the self-similar shape for energies higher than 2 keV. These results obtained for the LHS have relevant implications. The self-similar shape of the > 2 keV spectra implies that photons of these energies are produced (upscattered) in the same geo-
Independently of the continuum adopted model the PS, which correlates with the photon spectral softening (see effect shown in Figure 8 is the shift to higher frequencies of because we find the best signal to noise ratio in the 4–10 keV energy band. Note that the 4–10 keV band was chosen with that related to the time interval from I101 to I107 in the LHS PS derived in the time interval from I101 to I107 (8–15 keV), and 4.2 × 10^{-4} (15–200 keV).

(A color version of this figure is available in the online journal.)

As we have already demonstrated in Section 3, the energy spectral behavior (Figure 3), even within TOO-1, shows a slight softening from the time interval I105 to I111. In order to see the effect of this softening in the PS, we have compared the 4–10 keV PS derived in the time interval from I101 to I107 with that related to the time interval from I109 to I112 in the 4–10 keV energy band. Note that the 4–10 keV band was chosen because we find the best signal to noise ratio in this interval.

The result is presented in Table 7 and in Figure 8. The main effect shown in Figure 8 is the shift to higher frequencies of the PS, which correlates with the photon spectral softening (see Figure 3). Independently of the continuum adopted model the LF QPO centroid frequency increases while the continuum noise in this interval

![Figure 7](image-url)  
**Figure 7.** Top panel: LHS PSs in different energy bands (see the bottom panel for the correspondence between color and energy intervals). The decrease of the variability power with energy is evident from this figure. Bottom panel: LHS PSs as above, shifted, for clarity of display, along the ordinate direction by different factors, depending on the energy interval: factor 1 (0.1–2 keV), 0.4 (2–4 keV), 2.5 × 10^{-2} (4–10 keV), 7.1 × 10^{-3} (8–15 keV), and 4.2 × 10^{-4} (15–200 keV).

(A color version of this figure is available in the online journal.)

metrical configuration. Following TSA07, the break frequency found in the LHS PS is related to a diffusion time of perturbation propagation while the QPO low frequency is an eigenfrequency of the volume (magnetooacoustic) oscillation of the medium (in our case it is a Compton cloud). Our results show that the values of these PS characteristics are similar in all PSs for photon energies higher than 2 keV.

![Figure 8](image-url)  
**Figure 8.** LHS PSs of XTE J1650–500 in the time intervals from I101 to I107 and from I109 to I112 (see the text for details). The PS (red line) corresponding to the softer energy spectrum is shifted to higher frequencies with respect to that (blue line) corresponding to the hard energy spectrum (see the related energy spectra in Figure 3). The fit with a superposition of two Lorentzians is also shown. Best-fit details are shown in Table 6.

(A color version of this figure is available in the online journal.)

Table 4

| Components | 0.1–2 keV | 2–10 keV |
|------------|-----------|----------|
| Hard state (TOO-1) | | |
| QPO1, ν_{QPO1} (Hz) | 23 ± 2 | 1.55 ± 0.08 |
| QPO2, ν_{QPO2} (Hz) | 3.08 ± 0.07 | |
| Soft state (TOO-2) | | |
| QPO1, ν_{QPO1} (Hz) | 36 ± 3 | |
| QPO2, ν_{QPO2} (Hz) | | |

**Notes.**

a The model is a superposition of two broad Lorentzians (Lh, Lb) plus one or two narrow Lorentzians (L_{QPO1}, L_{QPO2}). Parameters in square parentheses are frozen in the fits. Errors are given at the 90% confidence level. See the text about the identification of the Lh component.

b See Section 4.1, for details about the identification of the Lb component.

Table 5

| Components | 0.1–2 keV | 2–4 keV | 4–10 keV | 8–15 keV | 15–200 keV |
|------------|-----------|---------|----------|----------|------------|
| Hard state (TOO-1) | | | | | |
| Lh, ν_{Lh} (Hz) | 0.59^{+0.06}_{-0.13} | 0.38^{+0.08}_{-0.04} | | | |
| Lb, ν_{Lb} (Hz) | 23 ± 2 | 2.1 ± 0.2 | 2.5^{+1.5}_{-0.5} | 3.5^{+1.4}_{-0.8} | 3.3^{+1.9}_{-0.9} |
| L_{QPO1}, ν_{QPO1} (Hz) | 1.54^{+0.07}_{-0.06} | [1.54] | | | |
| L_{QPO2}, ν_{QPO2} (Hz) | | | | | |

**Notes.**

a Parameters in square parentheses are frozen in the fits. Errors are given at the 90% confidence level.
b See Section 4.1 for details about the identification of the Lh component in the 0.1–2, 2–4, 4–10, 8–15, and 15–200 keV energy intervals.
remains stable in its shape. For the diffusion model continuum, as can be seen from Table 7, the LF QPO frequency increases from 1.47 ± 0.03 Hz to 1.66 ± 0.08 Hz (uncertainties at 90% confidence level).

In order to illustrate the evolution of the PS from TOO-1 to TOO-2, when the energy spectra undergo their transition from the LHS to the HSS (see I125 and I126 spectra in Figure 3), we compared the LHS PS with the HSS PS in two energy bands where the signal is highest: 2–10 keV and 0.1–2 keV (see the top-left and top-right panels of Figure 6, respectively). As can be seen from this figure, the relative power of the HSS PS (with respect to the LHS PS) and its shape strongly depend on the energy band.

We find (see Table 8) that the 0.1–2 keV HSS PS is well described by the sum of a PL plus a bknpl, with no evidence of QPOs in contrast to the 0.1–2 keV LHS PS which is described (see Table 6) by a bknpl plus a high (νb ∼ 14 Hz) frequency broad Lorentzian (FWHM∼ 40 Hz). On the other hand, the 2–10 keV HSS PS (see Table 8 and Figure 6) can be fit with a PL plus with a constant, while the 2–10 keV LHS PS is fit with a bknpl plus two narrow Lorentzians, one of which is consistent to be the second harmonics of the other at νb ∼ 1.5 Hz.

These results confirm what was previously found by Homan et al. (2003) using RXTE data, that there are prominent QPO features in XTE J1650–500 PS (see also Revnivtsev & Sunyaev 2001; Wijnands et al. 2001).

In the LHS, the Comptonization component is dominant and thus we should detect the X-ray emission along with its variability related to the Comptonizing (Compton cloud) contraction during the LHS–HSS transition (see TSA07). Following TSA07, we can interpret the VLFN component observed in the HSS as related to the timing response of the extended disk, while bknpl or Lb (in terms of the Lorentzian model) is associated with mass accretion rate perturbations in the Compton cloud (see the HSS PS in the right panels of Figure 6).

We find that in the 0.1–2 keV band not only vbb,max (using the Lorentzian model) but also vbr (using the diffusion model) increase from TOO-1 (LHS) to TOO-2 (HSS) by a factor of 60 (vbb max increases from 0.59±0.06 Hz to 36 ± 3 Hz, while vbr increases from 0.28 ± 0.03 Hz to ∼ 17 Hz). This high shift of the related frequencies is in agreement with the corona (Compton cloud) contraction during the LHS–HSS transition (see TSA07). Searching in the literature, we found that in Cyg X-1 PSs the break frequency changes from ∼ 0.03 Hz to ∼ 18 Hz value when photon index varies from 1.5 to 2.1 (see Figure 8 in Table 6 Best Model Fit Parameters used to Fit the PSs of TOO-1 in Different Energy Bands a

| Parameter    | 0.1–2 keV | 2–4 keV | 4–10 keV | 2–10 keV | 8–15 keV | 15–200 keV |
|--------------|-----------|---------|----------|----------|----------|------------|
| α1           | [0.]      | [0.]    | [0.]     | [0.]     | [0.]     | [0.]       |
| α2           | 0.7 ± 0.1 | 1.20 ± 0.02 | 1.05 ± 0.04 | 1.098 ± 0.013 | 0.96 ± 0.03 | 0.49 ± 0.10 |
| νb (Hz)      | 0.28 ± 0.03 | 0.345 ± 0.016 | 0.36 ± 0.03 | 0.35 ± 0.01 | 0.37 ± 0.04 | 0.4 ± 0.4 |
| FWHM L (Hz)  | 14.7 ± 0.7 | 1.49 ± 0.09 | 1.52 ± 0.04 | 1.53 ± 0.03 | 1.54 ± 0.04 | 1.54 ± 0.15 |
| FWHML (Hz)   | 30 ± 0.014 | 1.1 ± 0.3 | 0.8 ± 0.3 | 0.9 ± 0.2 | 0.46 ± 0.18 | 1.1 ± 1.4 |
| νb (Hz)      | ...       | [2νb/1] | [2νb/1]  | [2νb/1]  | [2νb/1]  | [2νb/1]    |
| χ²/dof       | 676.86/86 | 144.1/140 | 117.8/106 | 192.6/182 | 95.9/68  | 8.6/13     |

Note. a The model: bknpl + lorentzian1 + lorentzian2. Parameters in square parentheses are frozen in the fits. Errors are given at the 90% confidence level.

Table 7 Best-Fit Parameters of the Models used to Fit the PSs in Two Different Time Intervals (I101–I107, I109–I112) of TOO-1 in 4–10 keV a

| Parameter  | I101–I107  | I109–I112 |
|------------|------------|-----------|
| α1         | [0.]       | [0.]      |
| α2         | 0.961 ± 0.025 | 1.23 ± 0.12 |
| νb (Hz)    | 0.35 ± 0.03 | 0.37 ± 0.07 |
| νL (Hz)    | 1.47 ± 0.03 | 1.66 ± 0.08 |
| FWHML (Hz) | 0.63 ± 0.25 | 1.2 ± 0.7 |
| νL (Hz)    | [2νL/1]   | [2νL/1]  |
| FWHML (Hz) | 0.5 ± 0.2 | 0.9 ± 0.6 |
| χ²/dof     | 110.4/107 | 32.6/42   |

Note. a Model: bknpl + lorentzian1 + lorentzian2. Parameters in square parentheses are frozen in the fits. Errors are given at the 90% confidence level.

Table 8 Best-Fit Parameters of the Models used to Describe the PSs of TOO-2 (HSS) a

| Model       | 0.1–2 keV       | 2–10 keV       |
|-------------|-----------------|----------------|
| PL + bknpl  | α               | 1.0 ± 0.3       |
|             | Nbr (4.0×10^4)  | ...            |
|             | α2              | [0.]           |
|             | Nbr (1.0×10^3)  | ...            |
|             | νb (Hz)         | 17 ± 2         |
|             | Nbr (2.0×10^3)  | ...            |
| PL + const  | α               | ...            |
|             | Nbr (3×10^4)    | ...            |
|             | CONST           | (1.29 ± 0.35)×10^-5 |
|             | χ²/dof          | 126/102        |

Note. a In 0.1–2 keV, two models—1st model: PL + bknpl; 2nd model: PL + constant. The first index of the bknpl was fixed to 0. In 2–10 keV. Errors are given at the 90% confidence level.
The relative contribution of the Comptonization component (in the resulting spectrum) decreases when the source undergoes the hard-to-soft spectral transition (see Figure 3). We interpret this as a result of contraction of the Comptonization region (Compton cloud) during this spectral evolution (see Titarchuk et al. 1998, hereafter TLM98; TF04). We can infer this contraction effect using our best-fit model parameters. One of the parameters of the BMC model is the normalization of the BB component $C_N$, which is directly related to the effective area $A^\text{eff}$ of the BB emission [$A^\text{eff} \propto C_N/(T^4_\text{bb}(1 + A))$]. If we multiply this effective area with the fraction of Comptonized component $f = A/(1 + A)$, we obtain the effective area of the high-energy X-ray emission region (the Compton cloud). Using the best-fit values for the LHS and HSS spectra, we find that the area of the Compton cloud decreases by a factor of 5 during the transition from the LHS to the HSS (see Figure 9).

Furthermore in Figure 10, we demonstrate how the Comptonization fraction $f$ decreases when the photon index increases. This correlation presents one more argument for a Compton cloud contraction during LHS–HSS evolution. While in Section 4 we argued this contraction effect using the PS analysis only, here we find more arguments for this contraction using the energy spectrum analysis.

Actually, the PSs follow the energy spectral evolution. The PSs related to the softer energy spectra are weaker and shifted to higher frequencies with respect to those related to the harder spectra. It leads us to the conclusion that the emission area (CC) does contract when the source undergoes the hard-to-soft state transition.

Furthermore, TLM98 argued that the size of CC strongly depends on the Reynolds (Re) number of the accretion flow, and not on just the mass accretion rate. In other words, the LHS–HSS transition should be dictated by Re-number values, which is low in the LHS and high in the HSS, and the CC size decreases when the Re number increases. TS08 check this TLM98 prediction using Cyg X-1 observations by RXTE. First, they find a method to infer the Re number of the accretion flow using the observations. Then, they demonstrate that when the Re number increases all characteristic frequencies of the PS are
indeed shifted to higher values as a result of Compton cloud contraction during the LHS–HSS transition.

It is well known from the observations of X-ray BH binaries (see e.g., Wijnands & van der Klis 1999; ST06; ST07; KVK08) that the PS evolve along with the photon spectra. Here we find that our results for XTE J1650–500 are related to the findings by ST06 for Cyg X-1, where the authors, analyzing ~ 10 years of observational data from RXTE archive, found strongly correlated characteristics of PS and photon spectra (photon index). We have to admit that our claims of temporal and spectral correlation in XTE J1650–500 are based on only the limited set of the BeppoSAX data, while the results of the extensive RXTE data set for XTE J1650–500 by Shaposhnikov & Titarchuk (2008), hereafter ST08, do indicate a strongly correlated temporal and spectral evolution in this source.

This suggests that the underlying physics of the radiative and oscillatory processes is common in X-ray BH binaries. The consistency of the Comptonization model also suggests that their spectra emerge from similar Compton cloud geometric configurations whose sizes shrink during the state transition. The disk becomes more powerful at softer states and the cooling of Compton cloud is mostly dictated by the strong soft disk emission. The photon field and surrounding plasma are almost in equilibrium: the plasma temperature is the same order of the photon BB color temperature (of a few keV). The converging flow located in the innermost part of compact cloud is the only place where photons can be upscattered to energies of order of $m_e c^2$ and higher due to the dynamical Comptonization.

In the HSS PSs, we see the presence of two noise components: VLFN and bknpl (or $L_{\text{VLFN}}$ and $L_b$ in terms of the Lorentzian model). We suggest that the VLFN component is associated with the extended disk and bknpl is presumably formed as a result of the diffusive propagation of the mass accretion rate perturbation in the compact Compton cloud. In the LHS PS, only bknpl is observed, while the VLFN related to the disk component, presumably very weak and at very low frequencies, cannot be observed in the BeppoSAX data.

We also show that in XTE 1650–500 the power of X-ray variability drastically decreases toward the HSS. Note that this effect has been known for a number of BHs (see KVK08 and TS08 for details of the observations and explanation of this effect, respectively). The relative power of the HSS PS with respect of that in the LHS clearly depends on the energy bands. We present (for the first time in the literature) energy-dependent PSs of X-ray emission using BeppoSAX data. Although we find a noticeable dependence of the PS strength on energy, the PS shape is found to be almost self-similar in different energy bands (at least for the LHS PSs).

Moreover, we show that the break and QPO low frequencies of the XTE J1650–500 PSs, which we derived, correlate with the spectral state, in particular with the $\pi$, photon index of the energy spectrum. We succeed to determine the LF QPO corresponding to two different LHS spectra (indices): $\nu_{\text{QPO}} = 1.47 \pm 0.05$ Hz, $1.66 \pm 0.08$ Hz related to $\Gamma = 1.74 \pm 0.01$ and $1.79 \pm 0.06$, respectively. Thus, our data points based on BeppoSAX data for XTE J1650–500 are consistent with the index–QPO correlation found by ST08, based on the RXTE data for XTE J1650–500.