Detection of distinct power spectra in soft and hard X-ray bands in the hard state of GRS 1915+105

H. Stiele† and W. Yu
Shanghai Astronomical Observatory and Center for Galaxy and Cosmology, 80 Nandan Road, Shanghai 200030, China

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ABSTRACT

The well-known black hole X-ray binary GRS 1915+105 is a unique source in the sense that it cannot be classified within the standard picture of black hole binary states. In this work, we study archival XMM–Newton observations taken between 2003 and 2004 of the χ variability class of GRS 1915+105, which corresponds to the hard state in the standard black hole X-ray binary state classification. The crucial point of our study is that by using XMM–Newton data, we can access the variability below 3 keV, an energy range that is not covered with RXTE.

We focus on the study of the power spectral shape in the soft and hard X-ray band, in light of our work done with Swift on MAXI J1659−152. In the hard band (above 2.5 keV), power density spectra consist of band-limited noise and quasi-periodic oscillations, corresponding to the power spectral shape seen in the hard or intermediate state, while in the soft band the averaged power density spectrum is consistent with a power-law noise, corresponding to the power spectral shape usually seen in the soft state. The coexisting of two different power spectral shapes in the soft and hard band, where the soft-band power spectrum is dominated by a power-law noise, is consistent with MAXI J1659−152, and confirms the energy dependence of power spectral states. Our additional spectral analysis shows that the disc component does contribute to the soft-band flux. These findings support that the observed black hole power spectral state depends on which spectral component we are looking at, which implies that power spectral analysis is probably a more sensitive method than spectral modelling to trace the emergence of the disc component in the hard or intermediate state.

Key words: black hole physics – binaries: close – X-rays: binaries – X-rays: individual: GRS 1915+105.

1 INTRODUCTION

The known population of low-mass black hole X-ray binaries mainly consists of transient sources that can be studied only during outburst, as they are too faint to detect their variability reliably with present X-ray instruments during quiescence (see e.g. Garcia et al. 1998). The outbursts begin and end in the so-called low-hard state (LHS) and in between there is normally a transition to the high-soft state (HSS). All these states show characteristic timing and spectral properties. In the LHS, the rms variability is larger than 10 per cent and the power spectrum shows one or more band-limited noise (BLN) components and sometimes a specific timing feature named type-C quasi-periodic oscillations (QPOs) can be observed (Belloni, Motta & Muñoz-Darias 2011). The power spectrum of the HSS is well described by a power-law noise (PLN) component, sometimes with a break around 10 Hz, and the rms variability is at a few per cent (Homan et al. 2001).

In a recent study (Yu & Zhang 2013), we showed an energy dependence of the power spectra in the black hole candidate MAXI J1659−152. The source was unique in several respects. The spectral evolution was slow and the source was at a high latitude, allowing us to study the emergence of the soft disc component and how the soft component came in just before the transition to the soft state. We investigated energy and power density spectra (PDS) of Swift/XRT (0.3–2 keV) and RXTE/PCA (2–60 keV) observations that covered the outburst rise from the LHS to the HSS. During the LHS, the PDS in the 0.01–20 Hz range can be well described by BLN and QPOs in both, the soft and the hard, X-ray bands. With the onset of the hard intermediate state, which coincided with a disc fraction exceeding ~30 per cent in the 0.3–2.0 keV range, 1

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† E-mail: hstiele@shao.ac.cn

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this changed dramatically. While BLN and QPOs are still present above 2 keV, below 2 keV the power spectra are now dominated by PLN, as commonly observed in the HSS. This suggests that the photons responsible for the BLN and the QPO origin from the innermost hot flow subjected to Comptonization, while the photons responsible for the PLN can be related to the optically thick disc. Furthermore, we tried to constrain cut-off energies for the PLN and BLN plus QPO components, investigating contributions of each component in the 2–4 keV XRT band and at Proportional Counter Array (PCA) energies below 5 keV. Based on these investigations, we could constrain the cut-offs to occur in the 2.8–3.5 keV range.

The well-known black hole low-mass X-ray binary GRS 1915+105 (for a review, see Fender & Belloni 2004) was initially discovered by the WATCH instrument on board GRANAT in 1992 (Castro-Tirado, Brandt & Lund 1992). Since then, GRS 1915+105 has been observed densely at different wavelength ranges. A systematic monitoring in the X-rays revealed a rich pattern of variability on all time-scales. Belloni et al. (2000) identified 12 classes of variability and showed that, though complex, the behaviour of GRS 1915+105 can be understood as transitions between three basic spectral states A, B and C. Despite its many distinct accretion states, GRS 1915+105 appears similar to other black hole binaries (Reig, Belloni & van der Klis 2003; van Oers et al. 2010, and references therein). The closest analogue to the conventional canonical ‘low hard’ state in other X-ray binaries is the χ variability class, that is found exclusively in the C state (Pahari et al. 2013c). In this state, low-frequency QPOs are present (Chen, Swank & Taam 1997), whose energy spectrum consists with that of the hard component (Markwardt, Swank & Taam 1999). Correlations of the centroid frequency with the power-law index (Vignarca et al. 2003) and with the inner-disc radius (Rodriguez et al. 2002a,b) have been conducted and it was shown that the centroid frequency correlates positively with the flux of the disc component (Muno, Morgan & Remillard 1999). For completeness, we would like to mention that with IGR J17091−3624, a second source is known, which shows variability similar to the variability classes observed in GRS 1915+105 (Altamirano et al. 2011; Capitanio et al. 2012; Wijnands, Yang & Altamirano 2012; Pahari et al. 2013a,b).

In this paper, we make use of archival XMM–Newton observations to study the properties of PDS in different energy bands. Specifically, we intend to study the power spectra of the soft disc component in the energy range below ~2 keV and to check if the soft band variability in the χ class is indeed not only different from that in the hard band but also shows a PLN component similar to that in the soft state.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 XMM–Newton

XMM–Newton observed GRS 1915+105 several times in 2003, 2004 (Martocchia et al. 2006) and 2007. All but one of these observations are taken with the pn detector in burst mode. This mode was chosen because of the high source flux of GRS 1915+105. The only observation which has been taken with EPIC/pn in Timing mode (2004 April 17) suffers from frequent telemetry drop-outs and can hence not be used in our timing study (see also Martocchia et al. 2006).

For our study, we selected five observations of GRS 1915+105 being in the χ variability class. Details on these observations can be found in Table 1. We used the standard SAS (version 13.0.0) tools to filter and extract pn event files, paying particular attention to extract the list of photons not randomized in time. For our timing study, we selected the longest, continuous exposure available in each observation (see Table 1), i.e. the longest available standard good time interval. As all observations are taken in burst mode, we selected photons from a 15 column wide strip in RAWX centred on the column with the highest count rate, and we impose RAWY < 150 to avoid direct illumination by the source. We selected single and double events (PATTERN=4). We made use of the SAS task epatplot to investigate whether the observations are affected by pile-up. As there is a clear deviation from the theoretical predictions at energies below 1.5 keV, we focused our investigations on energies above 1.5 keV, where the observed pattern distributions follow the theoretical predictions. Applying this selection, we only exclude 3–4 per cent of the source photons, as GRS 1915+105 is highly absorbed at energies below 1.5 keV (see Martocchia et al. 2006). All values given in this paper are 1σ values.

2.1.1 Timing analysis

We extracted PDS for each observation in four energy bands: 1.5–2.5 keV, 2.5–3.5 keV, 3.5–4.5 keV and 4.5–8.0 keV. These four energy bands contain about 15 per cent, 20 per cent, 20 per cent, 35–40 per cent of the source photons, respectively. We investigated the noise level at frequencies above 30 Hz and found that it is consistent with 2, as expected for Poissonian noise (Zhang et al. 1995). We subtracted the contribution due to Poissonian noise, normalized the PDS according to Leahy, Elsner & Weisskopf (1983) and converted to square fractional rms (Belloni & Hasinger 1990). As in Yu & Zhang (2013), the PDS were fitted with models composed of a PLN, zero-centred Lorentzians for BLN components and Lorentzians for QPOs.

2.1.2 Spectral investigation

We also extracted energy spectra from all XMM–Newton observations, following the procedure to extract spectra from XMM–Newton burst mode data outlined in Kirsch et al. (2006). As for the timing study, we selected source photons from a 15 column wide strip in RAWX centred on the column with the highest count rate, including single and double events. Of course, no energy selection has been applied here, and we used RAWY < 140 as suggested by Kirsch et al. (2006). Background spectra have been extracted from columns 3 to 5.

Energy spectra obtained from XMM–Newton EPIC-pn fast-readout modes are known to be affected by gain shift due to charge-transfer inefficiency (CTI) which leads to an apparent shift of the instrumental edges visible at low energies. This shift can be corrected by applying the SAS task EPFAST to the data. However, EPFAST is likely unsuited to do CTI corrections at higher energies at present.
as it applies an energy-independent correction, which leads to an overcorrection at higher energies. This leads to a striking difference between the RXTE/PCA and the EPFAST-corrected XMM–Newton pn spectra. In contrast, the unmodified XMM–Newton spectrum is quite similar to the RXTE/PCA spectrum. This deviation of the spectral shape above ~6 keV due to the application of EPFAST has been already reported for simultaneous XMM–Newton and BeppoSAX data (Walton et al. 2012).

### 2.2 RXTE

For three of the XMM–Newton observations (Obs. B, C and E), RXTE data taken on the same day are available. Details on the observation with the longest exposure taken on the same day as an XMM–Newton observation are given in Table 2. For the remaining two XMM–Newton observations (Obs. A and D), the RXTE observation located closest in time is two days away. We refrain from including these observations in our study.

#### 2.2.1 Timing analysis

The variability study of the RXTE observations is based on data from the PCA. We computed PDS for each observation following the procedure outlined in Belloni et al. (2006). PDS production has been limited to the PCA channel band 0–35 (2–15 keV) and used 16 s long stretches of Event mode data. As for the XMM–Newton data, we subtracted the contribution due to Poissonian noise (Zhang 1995), normalized the PDS according to Leahy et al. (1983) and converted to square fractional rms (Belloni & Hasinger 1990).

#### 2.2.2 Spectral investigation

We used the PCA Standard 2 mode (STD2), which covers the 2–60 keV energy range with 129 channels for the spectral analysis. The standard RXTE software within HEASOFT V. 6.13 was used to extract background and dead-time corrected energy spectra for each observation, following Stiele et al. (2012). Solely Proportional Counter Unit 2 from the PCA was used since only this unit was on during all the observations. To account for residual uncertainties in the instrument calibration, a systematic error of 0.6 per cent was added to the PCA spectra.2

### 3 RESULTS

#### 3.1 PDS above 2.5 keV

We fitted the PDS using a model consisting of a zero centred Lorentzian for the BLN. In the XMM–Newton 4.5–8 keV band, QPOs are clearly visible in each observation (see Fig. 1, and Table 3), which have been fitted with a Lorentzian centred on the QPO frequency. The centroid frequencies lie in a range of 0.6–1.2 Hz. The fit statistics with this model is of \( \chi^2 / \nu = 28/26, 30/25, 16/21, 17/27, 23/25 \) for Obs. A–E, respectively. In Obs. A and B, there is an excess at low frequencies. Fitting it with a power law yields a non-significant component and a change in the fractional rms of ~0.3 per cent in Obs. B. Adding a power-law component in Obs. A affects the fit of the whole spectrum and leads to a decrease of the overall variability by ~3.0 per cent.

The feature observed in the PDS of the 4.5–8 keV band (BLN and QPOs) are also detected in the 2.5–3.5 keV and 3.5–4.5 keV bands, and the model used for the highest energy band gives also decent fits of the PDS in these bands. In these energy ranges, no additional power-law component is needed in Obs. A and B. The parameters obtained for the BLN and QPO in all three energy bands above 2.5 keV are given in Table 3.

In Fig. 2, rms spectra of all five XMM–Newton observations and for comparison the rms spectra of the RXTE observations are shown. The rms spectra of the main QPO obtained from RXTE data show a monotonic increase with energy and a flattening towards higher energies (which has been observed in previous studies; e.g. Rodriguez et al. 2004). In Obs. A, C and E, the rms variability is highest in the 3.5–4.5 keV band. While the rms values obtained from XMM–Newton and RXTE in Obs. B are consistent within errors, the XMM–Newton values in Obs. E are systematically higher than those obtained from RXTE data. The discrepancy of the XMM–Newton and RXTE rms values in the 3.5–4.5 keV band in Obs. C is most likely related to the poor determinability of the contribution of the BLN component in this energy band. In Obs. D, we observe a monotonic increase in the rms variability of the main QPO peak with energy. We also noticed that in the 2.5–3.5 keV band the QPO peak is broader than in the 4.5–8 keV band.

Inspired by the results obtained for the PDS below 2.5 keV (see Section 3.2), we tried to fit the PDS in the 2.5–3.5 keV band using a model, where we substitute the zero centred Lorentzian for the BLN with a power-law component. With this substitution the Lorentzian component to fit the upper harmonic is no longer needed. The rms variability of the upper harmonic in Obs. D and E is lowest in the 3.5–4.5 keV band, and a similar behaviour is observed in Obs. B. For all observations, the centroid QPO frequency stays constant within errors in all bands.

In addition, we investigated the PDS of the three RXTE observations in the 4.9–14.8 keV range using the same frequency range as for the XMM–Newton observations (1.8 \( \times 10^{-3}–34 \) Hz). The PDS are shown in Fig. 3, and their overall shape agrees with the one found from XMM–Newton data. In the RXTE data, an upper harmonic is present in all three observations (parameters are given in Table 3), although it is less prominent in the first two observations than in the observation corresponding to Obs. E, where the upper harmonic is seen with XMM–Newton. In the third RXTE observation, an additional power-law component was needed to obtain an acceptable fit at the lowest frequencies. All three RXTE observations require the addition of a second upper harmonic to obtain acceptable fits.

#### 3.2 PDS below 2.5 keV

For the lowest energy band (1.5–2.5 keV), we had to average the PDS of all five observations to obtain decent fit statistics. Assuming a PLN, we obtained a decent fit, without statistical need of a zero centred Lorentzian component, with \( \chi^2 / \nu = 16/14 \) and a power-law index of 0.7\( ^{+0.2}_{-0.1} \). Furthermore, the QPO, seen clearly at energies

| No. | Obs. id. | Date    | Exp. (ks) | XMM obs. |
|-----|---------|---------|-----------|----------|
| 1   | 80127-02-03-00 | 2003 April 10 | 12.55 | B        |
| 2   | 70702-01-50-00 | 2003 April 16 | 3.37  | C        |
| 3   | 90108-01-06-00 | 2004 May 3   | 1.29  | E        |

Note. *corresponding XMM–Newton observation.

Table 2. Details of RXTE observations.
above 2.5 keV, seems not to be present in this energy band. The averaged PDS of the 1.5–2.5 keV band is shown in Fig. 4 together with the averaged PDS of the 1.5–8 keV band. Adding a Lorentzian component with the centroid frequency (1.37 Hz) and width fixed at the values obtained from a fit to the averaged PDS in the 1.5–8 keV band, we obtain a 1σ upper limit for the QPO amplitude of 7.2 per cent rms. This value lies a little bit below the QPO amplitude value at soft energies obtained from Rodriguez et al. (2004) for a similar centroid frequency, ∼8–9 per cent rms. However, the upper limit we obtained from the XMM–Newton data is not very stringent.
We also tried to fit the PDS with a zero centred Lorentzian instead of the power law, which results in a \(\chi^2/\nu\) of 11/14. We find a break frequency of the Lorentzian of 0.45–0.52 Hz, which is clearly below the break frequency of the Lorentzian in the 1.5–8 keV band (3.35–\(0.35_{-0.49}^{+0.52}\) Hz).

### 3.3 Spectral results

Furthermore, the presence of a power-law component in the PDS below 2.5 keV, which is commonly observed in the HSS where the energy spectrum is dominated by emission form the accretion disc, suggests that a disc component should be present in the energy spectra, as inferred from the study of MAXI J1659–152 (Yu & Zhang 2013). This is in contrast to the results presented in Martocchia et al. (2006), where only a reflected power-law component (but no direct disc emission) was need to obtain acceptable fits, using solely XM–Newton data. Hence, we fitted combined XM–Newton/EPIC-pn+RXTE/PCA spectra within ISIS V. 1.6.2 (Houck & Denicola 2000) in the 0.5–10 keV and 5–60 keV range. We fitted the spectra with the model used in Martocchia et al. (2006), consisting of a power law with reflection component (REFLEC in XSPEC) modified by cold absorption, several emission features and an additional component to model the 1 keV excess. Using an unmodified XM–Newton spectrum plus an RXTE/PCA spectrum or an EPFAST-corrected XM–Newton spectrum plus an RXTE/PCA spectrum, the features present in the data do not allow us to obtain a reduced \(\chi^2\) below 2 (see Section 2.1.2). To get formally acceptable fits, we applied EPFAST to the EPIC-pn spectrum and ignored energies above 11.6 keV.

The energy spectra and residuals of all five observations with corrected XM–Newton data are grouped to have a data set to contain at least 20 channels. The obtained photon index, inner disc temperature and inner disc radius are given in Table A and D at 11 and 14 keV, respectively. The obtained photon index, inner disc temperature and inner disc radius are given in Table A and D at 11 and 14 keV, respectively. The obtained photon index, inner disc temperature and inner disc radius are given in Table A and D at 11 and 14 keV, respectively.
2.5–3.5 keV band the contribution of the disc component reduces to a few per cent. This finding puts additional support on the presence of a power-law component in the PDS below 2.5 keV, as we found a PLN in MAXI J1659−152 at a disc fraction exceeding ∼30 per cent in the 0.3–2 keV band (Yu & Zhang 2013). It is worth noting that an extension of the power-law spectral component to soft energies is not physical. Using a simple power-law spectral component in the spectral fit would actually underestimate the disc component.

We used Obs. E, which has the longest exposure of all three XMM–Newton observations with simultaneous RXTE data, to verify that in all three cases – unmodified XMM–Newton spectrum plus RXTE/PCA spectrum, EPFAST-corrected XMM–Newton spectrum plus RXTE/PCA spectrum and EPFAST-corrected XMM–Newton spectrum below 6 keV plus RXTE/PCA spectrum above 5 keV – the addition of a multicolour disc blackbody component leads to a significant improvement of the fit.

4 DISCUSSION AND CONCLUSION

We studied archival XMM–Newton data of GRS 1915+105 during its χ variability class obtained in 2003 and 2004. The focus of our study was put on an investigation of the power spectral shape in different X-ray energy bands, in the light of our work done with Swift on MAXI J1659−152 (Yu & Zhang 2013). We found that while the PDS at energies above 2.5 keV is dominated by BLN plus QPO, corresponding to the power spectral shape seen in the hard or intermediate state, the PDS in the energy range between 1.5 and 2.5 keV shows PLN, which corresponds to the power spectral shape usually seen in the soft state. A similar existence of two distinct power spectral states, BLN plus QPO above 2 keV and PLN below 2 keV, has been found for MAXI J1659−152 in its hard intermediate state (Yu & Zhang 2013). Our result that the PDS of the χ class of GRS 1915+105 shows a similar energy dependence as the hard intermediate state in MAXI J1659−152 fits well into the known connection of the χ variability class in GRS 1915+105 with the intermediate state (preferentially close to the hard state) in other black hole X-ray binaries (Reig et al. 2003; Pahari et al. 2013c).

In the study of MAXI J1659−152, Yu & Zhang (2013) have found that the PLN in the soft band seems to have a cut-off at or below the QPO and BLN break frequency. The XMM–Newton data of GRS 1915+105 do not allow us to determine if there is such a cut-off. Studying RXTE PDS in individual energy bands,

Figure 2. Shown are rms spectra of the QPO of the five XMM–Newton χ variability class observations investigated in this study (frequency range: $1.8 \times 10^{-3}$–34 Hz). For both observations taken in 2004, the rms spectrum of the main QPO, as well as its upper harmonic (indicated by an ‘X’) is given. For comparison, the rms spectra of the main QPO and its upper harmonic derived from RXTE data are indicated by grey triangles and squares.
Figure 3. PDS of the three \textit{RXTE} observations in the 4.9–14.8 keV band. The best-fitting model is indicated by a solid line and the individual components are given as dashed lines. The letter in the upper-right corner indicates the corresponding \textit{XMM–Newton} observation.

only those of Obs. 3 (the one corresponding to \textit{XMM–Newton} Obs. E) show at energies below 4.5 keV a clear deviation from a BLN plus QPO shape at frequencies below \(\sim0.2\) Hz that can be described by a power-law component. The frequency at which the deviation from the BLN plus QPO shape occurs decreases with increasing energy. However, this finding does not allow us to draw conclusions on a possible cut-off in the 1.5–2.5 keV band, as the band covered by \textit{RXTE} is too broad (up to 4.5 keV, and data with a higher energy resolution are not available) and the presence of an additional PLN is only found in one out of three \textit{RXTE} observations.

In summary, the observations of GRS 1915+105 show similar energy-dependent power spectral states as in MAXI J1659–152, which means that two different power spectral shapes are coexisting in the hard and soft band simultaneously. In the soft band, which is contributed by emission from the thermal disc component, not only the variability amplitude is lower, as has been known before, but also the power spectral shape is of a power-law shape. Such an energy dependence reveals a geometry in which the photons in the soft energy band and in the hard energy band come from different locations in the system, i.e. the cold optically thick accretion disc and the region of Comptonization of hot electrons [being it either an optically thin hot corona (see e.g. Esin, McClintock & Narayan 1997) or a jet flow (see e.g. Markoff, Nowak & Wilms 2005)], respectively. The inner radius at which the cold disc component ends would be determined by future accurate measurements of the PLN in the soft band. Note that the radius at which the cold disc ends may be not the radius at which the cold disc terminates (as assumed in the truncation disc model; e.g. Dubus, Hameury & Lasota 2001; McClintock & Remillard 2006; Done, Gierliński & Kubota 2007), since a hot flow or corona would cover the innermost cold disc so the radius one determines from the cut-off frequency of the PLN would correspond to the radius to which the hot flow or corona extends (while the disc can reach down to the innermost stable circular orbit as assumed e.g. in Beloborodov 1999; Merloni & Fabian 2002; Miller et al. 2006; Reis et al. 2013).

In conclusion, the energy dependence of the power spectral state found supports the idea that the observed power spectral state depends on which spectral component (and thus the geometrical location – disc or corona) we are looking at, and that a multiwavelength picture of power spectra in black hole X-ray binaries is needed. The important consequence of such an energy-dependent picture of a black hole power spectral state is that power spectral analysis in the soft X-ray energy band is more sensitive to the
Figure 5. Energy spectra and residuals of all five XMM–Newton observations. For Obs. B, C and E the simultaneous RXTE/PCA data are included in the fit. The best-fitting model as well as the contribution of the disc blackbody emission and of the power law with reflection component are indicated by solid lines.

emergence of the disc component in the hard or intermediate state than energy spectral analysis, which in many circumstances is model dependent.

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Table 4. Selected spectral parameters.

| No. | $\Gamma$  | $T_{\text{in}}$ (keV) | $R_{\text{in}} \times D_{10}$ (km) |
|-----|-----------|-----------------------|----------------------------------|
| A   | 1.37$^{+0.03}_{-0.02}$ | 0.56$^{+0.05}_{-0.06}$ | 82$^{+21}_{-12}$ |
| B   | 1.85$^{+0.03}_{-0.02}$ | 0.23$^{+0.01}_{-0.01}$ | 3179$^{+255}_{-560}$ |
| C   | 1.62$^{+0.03}_{-0.02}$ | 0.18$^{+0.06}_{-0.05}$ | 1886$^{+12}_{-15}$ |
| D   | 1.32$^{+0.01}_{-0.02}$ | 0.32$^{+0.05}_{-0.02}$ | 337$^{+86}_{-133}$ |
| E   | 1.64$^{+0.02}_{-0.01}$ | 0.33$^{+0.02}_{-0.01}$ | 313$^{+51}_{-44}$ |

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