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Probing the disc corona connection in accreting black holes.

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X-ray spectral variability is a powerful probe of the relationship between the accretion disc and corona in accreting black holes. To date most efforts have concentrated on the relationship between reflection (iron line and continuum) and the X-ray power law, whilst the accompanying thermal reprocessing has been largely neglected. We have started a program to use rms spectra and a new analysis technique, the "covariance spectrum" to disentangle the different components of the X-ray spectra of black hole X-ray binaries, identify the relationship between disc thermal emission and the illuminating power law and place strong constraints on the geometry of the disc and corona. Here we present the first results from this study which show evidence for a fluctuating inner disc truncation radius in the hard states of SWIFT J1753.5-0127 and GX 339-4.

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1. Introduction

The spectra of Black Hole X-ray Binaries (BHXRB) in the low/hard state are characterised by hard power-law spectra due to Comptonisation in a hot corona and a weak, low temperature blackbody component from the accretion disc [1]. The weakness of the disc is usually taken to imply that it is truncated at large radii. Much of the previous work investigating the low/hard state has concentrated on fitting models to mean spectra, ignoring how the different model components vary with respect to each other on short timescales. In this work, we examine the variability spectra of two low-mass X-ray binaries, SWIFT J1753.5-0127 and GX 339-4 in the low/hard state. SWIFT J1753.5-0127 was discovered by the SWIFT Burst Alert Telescope (BAT) in May 2005 [2] and has been shown to be a short-period X-ray binary [3] which has remained active in the low/hard state since it was first observed [4]. GX 339-4 was one of the earliest proposed black hole candidates [5] and is now a well studied transient. Interestingly, GX 339-4 shows strong reflection features in its X-ray spectra [6], suggesting that the disc may extend down towards the innermost stable circular orbit (ISCO) in the low/hard state [7] contrary to the predictions of advection dominated accretion flow (ADAF) models [8]. There is no strong evidence for reflection features in SWIFT J1753.5-0127, but spectral fits to the blackbody component are suggestive of a disc extending close to the ISCO [9].

2. Observations and Data Reduction

SWIFT J1753.5-0127 was observed for 42 ks by *XMM-Newton* EPIC-PN on March 24th 2006 in *pn-timing mode* using the medium optical filter. The events list was screened using Keith Arnaud's perl script XMMCLEAN to select only events with FLAG=0 and PATTERN ≤ 4. Using SAS Version 7.0, EVSELECT was used to extract the mean spectrum, following the procedure of Miller et al. [7], between 20 and 56 in RAWX and using the full RAWY range. The SAS tasks ARFGEN and RMFGEN were used to generate ancillary response files and redistribution matrix files.

GX 339-4 was observed by *XMM-Newton* on 16th March 2004 during revolutions 782 and 783, again in *pn-timing mode*. using the medium optical filter. Data reduction was very similar, using SAS version 7.0, but care was taken to avoid pile up. Successive columns from the centre of the image were excised in RAWX and spectra extracted until no discernable difference in spectral shape could be identified. The pn data was deemed free of pile up using extraction regions in RAWX from 30 to 36 and 40 to 46 (i.e. Columns 37 to 39 inclusive were excised). Background spectra were selected in RAWX from 10 to 18 over the full RAWY range. To generate appropriate ancillary response files for this excised pn data it was necessary to use ARFGEN to generate an arf for the full region in RAWX from 30 to 46 and generate a second arf from the spectrum of the excluded region (RAWX 37 to 39) and then subtract the latter from the former using the command ADDARF[1].

[1]http://xmm.vilspa.esa.es/external/xmm_user_support/documentation/sas_usg/USG/node63.html

For both sources, we extracted data from *RXTE* observations which were contemporaneous with the *XMM-Newton* observations. We used high time and spectral-resolution PCA Event mode data to extract mean spectra and make rms and covariance spectra using the same time binning as the EPIC-pn data. Throughout this work we use *RXTE* PCA data in the 3-25 keV range, *XMM* data in the 0.7-10.0 keV range and allow RXTE spectral fits to be offset by a constant factor with respect to the simultaneous EPIC-pn fits, to allow for the difference in flux calibration between the PCA and EPIC-pn instruments.

2.1 RMS and Covariance Analysis

When fitting models to X-ray spectra, it is typical to use mean X-ray spectra that only describe the average properties of a source. However, such fits say nothing about the way in which different model components vary with respect to each other in time. The rms spectrum picks out the time varying components and a comparison of the mean and rms spectra can reveal differences in variable sources between the average properties of the source and its variable components. This type of analysis therefore provides a method of probing reflection and thermal reprocessing, which is the means by which hard X-ray photons emitted from a hot coronal inner region heat the cooler accretion disc. From such differences, one can start to place constraints on the geometry of the disc and corona in BHXRB.

Producing the rms spectrum involves allocating each event to a time and energy bin, dividing the light curve into segments consisting of *n* time bins per segment and then working out the variance in each segment for each energy bin according to the following standard formula:

$$\sigma_{XS}^2 = \frac{1}{(n-1)} \sum_1^n (X_i - \bar{X})^2 - \sigma_{err}^2$$

where X_i is the count rate in the ith bin and $\bar{X}$ is the mean count rate in the segment. The expected Poisson error is subtracted, leaving the "excess variance" in each segment. The excess variances can then be averaged over all of the segments of the light curve. The square root of the average excess variance plotted against energy forms the "rms spectrum"[2].

There is, however, a problem with the rms spectrum when variability or statistics are low, most notably at higher energies. It is possible for the Poisson error term to be larger than the variance term, producing negative average excess variances. If this is the case, it is not possible to calculate the rms at these energies and this introduces a bias towards higher rms values at higher energies. In order to overcome these problems, a new technique called the "covariance spectrum" can be used. In this technique the covariance is calculated according to the forumla:

$$\sigma_{cov}^2 = \frac{1}{(n-1)} \sum_1^n (X_i - \bar{X})(Y_i - \bar{Y})$$

[2]This is absolute (not fractional) rms, since we are not normalising by the mean count rate.

where Y_i now refers to a "reference band" running over some energy range where the absolute variability is largest in count rate units (e.g. 1.0 to 4.0 keV). The covariance spectrum therefore does not suffer from the same problems as the rms spectrum, as no Poisson error term has to be subtracted (uncorrelated noise simply cancels out). The covariance spectrum is plotted against energy as:

$$\sigma_{cov} = \frac{\sigma_{cov}^2}{\sqrt{(ref\ excess\ variance)}}$$

Therefore, the only requirement for there being a value of covariance at a given energy is that the reference excess variance is not negative. This is usually the case, since the reference band is chosen to include those energies with the largest absolute variability (always 1.0 to 4.0 keV in this work).

In the case of a particular energy bin, X_i would represent the count rate in the i^{th} time bin of the segment in the energy range of this energy bin, where as each Y_i would represent the count rate of the corresponding i^{th} time bin of the reference band including all photons in the energy range covered by the reference band. When the covariance is being calculated for an energy bin inside the reference band, the channel of interest is removed from the reference band. The reasoning behind this is that if the channel of interest is exactly duplicated in the reference band the Poisson error will not cancel and an unwanted correlation would appear. One can think of the covariance as a matched filter, where the variations in the good signal-to-noise reference band pick out much weaker variations in the energy channel of interest that are buried in noise. In this way the covariance spectrum picks out the components of the energy channel of interest that are correlated with those in the reference band.

It is important to note that the covariance spectra only picks out the correlated variability component and is therefore a more appropriate measure than the rms spectrum in constraining the reprocessing of hard photons to soft photons. When the rms and covariance spectrum are overlayed, they match closely indicating that the reference band is well correlated with all other energies. Another advantage of the matched filter behaviour of the covariance spectrum, is that it has smaller error bars than the rms spectrum.

3. Results and Data Analysis

Covariance spectra were produced for the *XMM timing mode* and *RXTE* observations of SWIFT J1753.5-0127 using bin sizes of 2.7s and 0.1s with 100 bins per segment and 40 bins per segment respectively. The mean and covariance spectra from *EPIC pn* and *PCA* data were fitted in *XSPEC* using a simple absorbed power law and the multicolour disc model DISKBB [10] (required by means of an F-test) with the disc temperature tied to be the same between the different spectra. A systematic of 1% was used in XSPEC during fitting, and the reduced chi squared of the fit was 0.92.

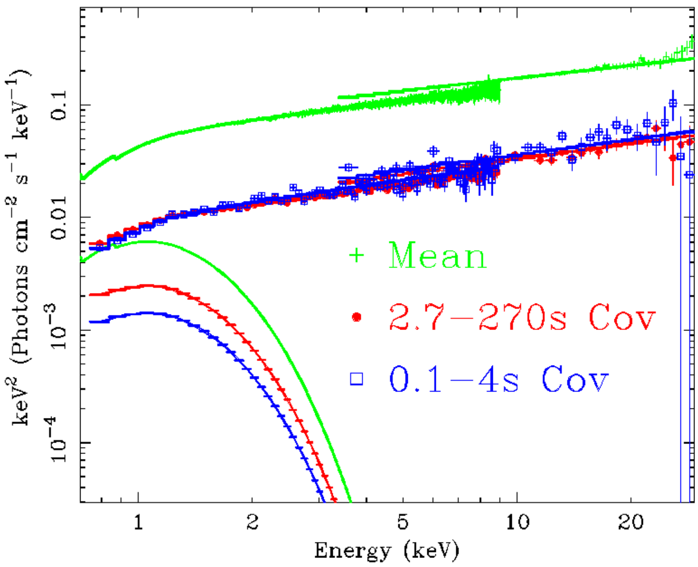

Figure 1: Unfolded spectrum fitted in XSPEC of SWIFT J1753.5-0127 showing the relative contributions of the black body and power law components.

Interestingly, the black body normalisation is larger relative to the power law component in the 2.7s covariance compared to the other spectra. This can clearly be seen by setting the black body normalisation to zero, as in figure 2, where there is an extra soft component in the variability spectra which is more pronounced in the longer timescales.

The above result can be verified in a model independent way by taking covariance ratios. This tends to cancel out effects of the detector response and, as can be seen in figure 3, shows the stronger soft component in the 2.7s covariance spectrum. There are at least two possible explanations for the variability observed in this source. The first is that a change is occurring in the disc-corona geometry giving rise to an increased thermal component when the power-law illuminates a larger fraction of the disc. The second explanation is that there is intrinsic variability in the optically thick disc emission. GX 339-4 has significant reflection features, and therefore any change in geometry will manifest itself as a change in the reflection components as the disc sees more power law. If it can be established that GX 339-4 exhibits similar behaviour to SWIFT J1753.5-0127, then the reflection properties can be used to disentangle these two possibilities.

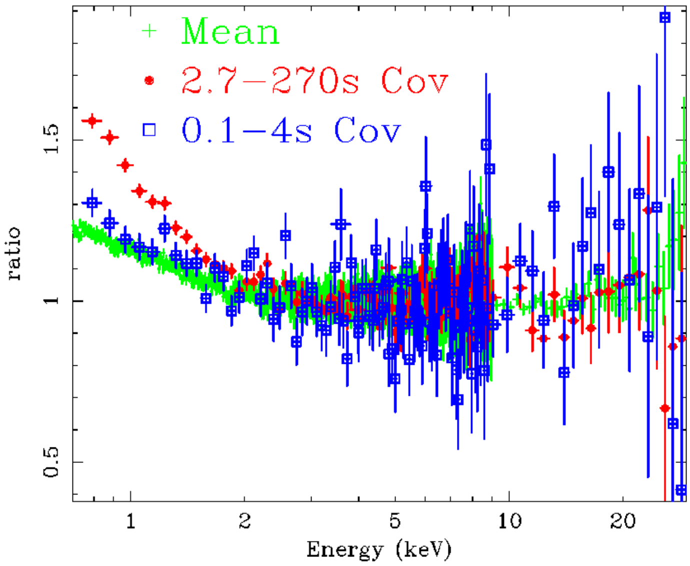

Figure 2: Data to model ratio plot with black body normalisations in the model set to zero in the mean and covariance spectra for SWIFT J1753.5-0127.

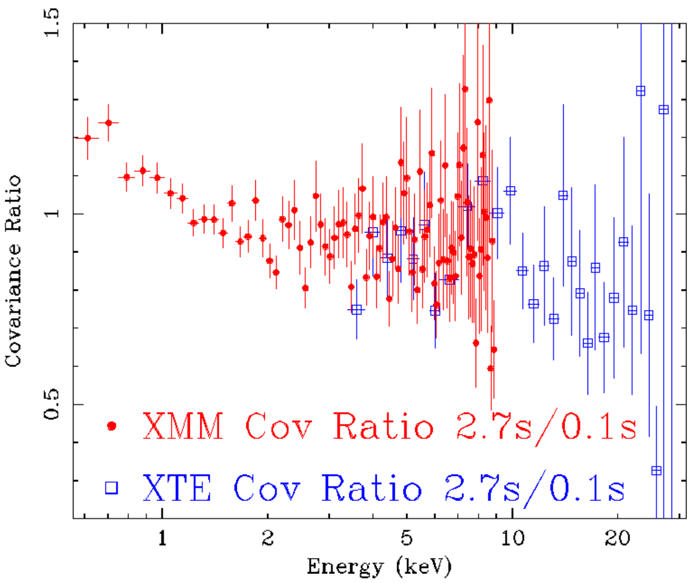

Figure 3: Covariance ratios for SWIFT J1753.5-0127 showing the extra thermal component on longer timescales.

The data for GX339-4 was difficult to work with due to pile up and apparent inconsistencies between the *MOS* and *PN* data. Therefore, the model independent approach of taking covariance ratios using *XMM* EPIC-pn data is used in figure 4 to illustrate that the same processes appear to be taking place in GX339-4 and SWIFT J1753.5-0127.

Fits were performed to the two *RXTE* covariance spectra in *XSPEC* for GX339-4 with a model including reflection (HREFL) and relativisitic blurring of the iron line (KDBLUR). The reflection normalisations were then set to zero and ratios plotted revealing very little change in the reflection component and associated iron line. The implication, therefore, is that in these two sources a possible explanation for the observed variability is variation in the intrinsic disc emission. This could be visualised as the inner edge of the optically thick disc moving in and out at the boundary layer between the disc and corona, producing variable intrinsic emission.

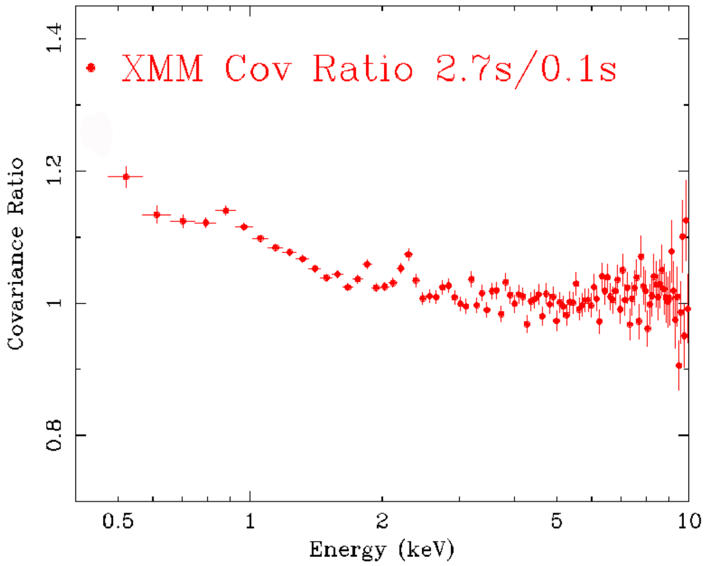

Figure 4: Covariance ratios for GX339-4 using *XMM* PN data illustrating the extra soft component on longer timescales, in agreement with SWIFT J1753.5-0127.

4. Conclusions

SWIFT J1753.5-0127 and GX339-4 have been shown to demonstrate an increased soft component in their variability spectra relative to the power law component, which increases on longer timescales. The similarity in the reflection components of 2.7s and 0.1s covariance spectra using *RXTE* data in GX 339-4 suggests that this thermal component is not related to changes in the disc-corona geometry. A possible explanation is that oscillation of the inner edge of the optically thick accretion disc is responsible for variations in intrinsic disc emission.

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