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The X-ray fast-time variability of Sco X-2 (GX 349+2) with RXTE

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ABSTRACT

Sco X-2 (GX 349+2) is a low-mass X-ray binary and Z source. We have analysed ~156 ks of Rossi X-ray Timing Explorer data, obtained in 1998 January, on this source. We investigated the fast-time variability as a function of position on the Z track. During these observations, Sco X-2 traced out the most extensive Z track ever reported from this object, making this the most comprehensive study thus far. We found the broad peaked flaring branch noise that is typical of Sco X-2, with a centroid frequency in the range 3.3–5.8 Hz. We also discovered low-frequency noise, and a new peaked noise feature, with centroid frequencies in the range 5.4–7.6 and 11–54 Hz, respectively. We discuss the phenomenology of these features, their relationship with the power spectral components found in other low-mass X-ray binaries, and the implications for current models. In particular, the low-frequency noise we observed was strongest at intermediate energies, in contrast to the low-frequency noise seen in other Z sources. We also detected very low-frequency noise, and have calculated complex cross-spectra between intensity and hardness. We found that the very low-frequency noise is not entirely a result of motion along the Z track.

Key words: accretion, accretion discs – binaries: close – stars: individual: Sco X-2 – stars: individual: GX 349+2 – stars: neutron – X-rays: stars.

1 INTRODUCTION

Sco X-2 is one of the persistently bright neutron star low-mass X-ray binaries known as Z sources. Z sources are so-named because, over time, they trace out a ‘Z’-shaped track in an X-ray colour–colour (CD) and hardness–intensity (HID) diagram. The top of the ‘Z’ is called the horizontal branch (HB), the diagonal is the normal branch (NB) and the bottom is the flaring branch (FB) (Hasinger & van der Klis 1989). Inferred mass-accretion rate increases from the HB, through the NB, to the FB. The mass-accretion rate is thought to reach the Eddington limit at the bottom of the NB, and is super-Eddington in the FB. The five other traditional Z sources are: Sco X-1, GX 17+2, Cyg X-2, GX 340+0 and GX 5−1. A related class of objects are the atoll sources; they exhibit a curved track in a colour–colour diagram (Hasinger & van der Klis 1989).

1.1 Z and atoll source fast-time variability

Through the study of the X-ray fast-time variability of low-mass X-ray binaries, we are able to investigate mass-accretion processes; in particular, the fast-time variability is a signature of the flow of matter near the compact object (see the review by van der Klis 2000). The typical power spectral properties of Z and atoll sources are correlated with position in the CD (Hasinger & van der Klis 1989; also van der Klis 1995a).

On the HB, Z sources typically exhibit six variability components that are phenomenologically related (e.g. Homan et al. 2002 and references therein): a band-limited noise component with cut-off frequency in the range 2–10 Hz, called low-frequency noise (LFN); a quasi-periodic oscillation (QPO) in the range 6–20 Hz; a second harmonic to the HBO; and a pair of QPOs in the range 60–110 Hz, called kHz QPOs.

On the NB and lower part of the FB there is a QPO in the range 6–20 Hz (e.g. van der Klis 1995a; Dieters & van der Klis 2000; Homan et al. 2002). On the NB, it is known as a normal-branch oscillation (NBO), and its frequency is roughly constant near 6 Hz. With movement through the NB/FB vertex the mean frequency and full-width at half-maximum (FWHM) of the QPO rise rapidly. It is then known as a flaring branch oscillation (FBO), and becomes indistinguishable from the underlying continuum at about 10–20 per cent of the way up that branch.

Some of the features seen in the HB are also sometimes seen on the NB and FB. In Sco X-1, van der Klis et al. (1997) found...
that the NBO appeared to ‘peak-up’ out of the LFN. In GX 17+2, Homan et al. (2002) found that the NBO and LFN existed simultaneously, and were separate features. They also observed a peaked noise feature in the FB, in addition to an FBO, which they identified as LFN.

A power-law noise component, called very low-frequency noise (VLFN), exists throughout the Z track, and is stronger at higher mass-accretion rates and at higher energies (e.g. van der Klis 1995a). van der Klis (1991) suggested that it is produced by the variations in intensity that are associated with movement along the Z track. Dieters & van der Klis (2000) constructed power spectra of rank number (see Section 2.1), in the frequency range $3 \times 10^{-3} - 0.01$ Hz, and also of intensity, in the range $8 \times 10^{-2} - 0.2$ Hz. They found that the power-law indices from the rank-number power spectra were consistent with those from the intensity power spectra, although we note that the uncertainties on the rank-number power-law indices were quite large. If VLFN is caused by movement along the Z track, then the speed of that movement should be correlated with the VLFN strength. Dieters & van der Klis (2000) found this to be the case in Sco X-1, Homan et al. (2002) found that the correlation exists in some parts of the Z track of GX 17+2, and Wijnands et al. (1997) found that the VLFN strength in Cyg X-2 did not vary monotonically with speed.

Finally, a noise component with a cut-off frequency in the range 30–100 Hz, called high-frequency noise (HFN), has also been observed (e.g. van der Klis 1995a).

At their lowest inferred mass-accretion rates atoll sources exhibit: a band-limited noise component, modelled using a broken power law with a break frequency in the range 0.1–32 Hz, called (rather confusingly) high-frequency noise; low-frequency QPOs or broad peaks in the range 1–67 Hz; and kHz QPOs. Except for the kHz QPOs, these features are very similar to those seen in black hole candidates (BHCs) (e.g. Wijnands & van der Klis 1999 and references therein). In atoll sources VLFN dominates at higher mass-accretion rates.

A correlation was found in Z sources and atoll sources between the frequencies of the kHz QPOs, and the HBO or 1–67 Hz QPO; the same correlation was found between features in the power spectra of BHCs (Psaltis, Belloni & van der Klis 1999a; see also Psaltis et al. 1999b). Wijnands & van der Klis (1999) discovered another correlation in atoll sources and BHCs, between the break frequency of the band-limited noise (the HFN in atoll sources), and the centroid frequency of a QPO or bump in the range 0.2–67 Hz (the 1–67 Hz QPO in atoll sources). The same correlation was found to exist in Z sources between the LFN and sub-HBO peak, and also between the sub-HBO and HBO peaks (Wijnands & van der Klis 1999; see also Homan et al. 2002), van der Klis (1994a,b), Belloni, Psaltis & van der Klis (2002) and Sunyaev & Revnivtsev (2000) have also made comparisons between the power spectra of BHCs and neutron star LMXBs.

There is currently much effort being put into developing models that can explain these correlations. The discovery that the power spectral components in black hole candidates follow the same correlations seen in Z sources and atoll sources gives support to those models that do not depend on the presence or otherwise of a solid surface or magnetic field (e.g. van der Klis 2000).

1.2 Scorpius X-2 (GX 349+2)

Except for the fact that Sco X-2 has never been observed in the HB, its hardness–intensity diagram looks nearly identical to that of Sco X-1 (e.g. Schulz, Hasinger & Trümper 1989). Therefore, one might expect the fast-time variability of Sco X-2 to be similar to that seen in Sco X-1.

Ponman, Cooke & Stella (1988) analysed EXOSAT data and found broad peaked noise in the FB, with a centroid frequency, FWHM and fractional rms amplitude of roughly 5, 10 Hz and 3 per cent, respectively. Kuulkers & van der Klis (1998) analysed a small RXTE data set and found that the peaked noise became narrower and moved to lower frequencies with movement from the NB into the FB. O’Neill et al. (2001a) analysed Ginga data, and found peaked noise with a centroid frequency and FWHM in the range 4–7 and 6–12 Hz, respectively. They found that it was strongest at about 10 per cent of the way up FB, and was present until halfway up the branch. They referred to the feature as flaring branch noise (FBN), and concluded that FBN is not the same as atoll source high-frequency noise; it is difficult to explain it with the model for typical normal/flaring branch oscillations (Fortner, Lamb & Miller 1989); and it resembles the peaked noise seen in the FB of Cyg X-2 at low overall intensities. O’Neill et al. (2001a) also found very low-frequency noise that became stronger with movement up the FB, as seen in other Z sources.

Zhang, Strohmayer & Swank (1998) observed Sco X-2 with RXTE in 1998 January. During those observations Sco X-2 traced out the most extensive Z track ever seen from that object; most importantly, it was found higher up in the NB than ever before. A pair of kilohertz quasi-periodic oscillations were detected at 712 and 978 Hz, respectively, in the uppermost part of the observed NB. Agrawal & Bhattacharyya (2001) analysed ~40 ks of RXTE data obtained in 1998 September and October and also found an extended NB. They detected peaked noise similar to that found in previous observations, though its fractional rms amplitude did not vary smoothly, and the feature was detected as high as 80 per cent of the way up the FB. They found that the properties of the peaked noise were similar throughout the Z track, and thus concluded that the peaked noise seen in the NB was the same as that seen in the FB. A QPO, with a centroid frequency of 3.8 Hz, was detected (90 per cent confidence level) in the FB during a dip in the intensity that occurred after a flare. During the September and October observations the behaviour of the VLFN was very different from that seen previously: it was, on average, stronger in the NB than in the FB, and did not exhibit an increase in strength with movement up the FB.

On the basis of phenomenology, the peaked noise observed in the NB and FB of Sco X-2 is unlikely to be an N/FBO (e.g. Agrawal & Bhattacharyya 2001 and references therein). First, the peaked noise seen in the NB of Sco X-2 is much broader than an NBO. Secondly, as Sco X-2 moves from the NB, through the NB/FB vertex, and then up the FB, the centroid frequency and FWHM of the peaked noise decrease, and then stay roughly constant. This is in contrast to an N/FBO, of which, with the same movement along the track, the centroid frequency and FWHM increase rapidly. Thirdly, the peaked noise in Sco X-2 has been seen as far as 80 per cent of the way up the FB, while FBOs are only present in the lowest 10–20 per cent of that branch.

Zhang et al. (1998) did not analyse the low-frequency fast-time variability in detail. We, therefore, decided to reanalyse those data. Our primary objectives were: to look for the LFN and HBO that are expected to accompany kHz QPOs; to better understand the phenomenology of FBN; to study the properties of the kHz QPOs as a function of both position on the Z track and photon energy; and, to further investigate VLFN. A preliminary account of this work has been given by O’Neill et al. (2001b).
A spline was fitted through the HID, and rank numbers were calculated for each point. The rank number is a one-dimensional measure of position in the Z track; it was introduced by Hasinger et al. (1990), and is symbolized as $S_i$ (Hertz et al. 1992; see also Dieters & van der Klis 2000). It is a measure of the inferred mass-accretion rate. We defined the NB/FB vertex as $S_i = 2$, and the top of the FB as $S_i = 3$.

Average power spectra were then constructed on the basis of rank number, and were normalized to give the fractional rms amplitude squared per Hz. The error given for each mean $S_i$ is the standard deviation of the rank numbers used in the average.

### 2.2 Fitting of power spectra

To investigate the low-frequency fast-time variability, we fitted the resultant power spectra in the range 0.0625–300 Hz using a power law to represent very low-frequency noise, Lorentzians as required to represent peaked noise and a constant to represent the deadtime-affected white-noise level. We investigated the kilohertz quasi-periodic oscillations by fitting the resultant power spectra in the range 500–1200 Hz, using two Lorentzians and a constant.

The VLFN fractional rms amplitude was measured by extrapolating the best-fitting power law and integrating over the range 0.01–1 Hz. The addition of a Lorentzian component to a model was deemed necessary only when the probability of exceeding the $\chi^2$ of the best-fitting model was $< 0.001$, and an F-test for the inclusion of the extra Lorentzian was significant at or above the 3$\sigma$ level. We fixed the centroid frequency and/or the FWHM of a Lorentzian component either when they could not be constrained, or when a fractional rms amplitude upper limit was being measured. Uncertainties in the best-fitting parameters were measured using $\Delta \chi^2 = 1$, and upper limits were measured using $\Delta \chi^2 = 2.71$ (95 per cent confidence level).

We corrected the best-fitting fractional rms amplitudes for differential deadtime and channel cross-talk as appropriate (see Appendix A). Finally, we corrected the fractional rms amplitudes for the background counting rate (e.g. van der Klis 1995b). In the low-frequency power spectra, the reduction of the rms owing to the binning of data was negligible; the binning correction factor applied to the rms of the kHz QPOs was 1.1 (van der Klis 1989).

### 2.3 Investigation of very low-frequency noise

To further investigate the VLFN, we constructed a HID from the single-bit and event-mode data using 32-s averages. We defined the hardness as the counting rate ratio between the energy ranges 8.7–40 keV and 6.5–8.7 keV, and the intensity as the counting rate in the range 2.0–19.7 keV. We calculated complex Fourier spectra from both the hardness light curve and the deadtime-corrected intensity light curve, using 1-s time resolution and 32-s intervals. Each interval, along with its associated Fourier spectrum, corresponded exactly to one point in the HID. We used 1-s time resolution so we could directly investigate the fast-time variability in the time domain. The Fourier spectra had a frequency range of 0.031–5–0.5 Hz.

For each 32-s interval we calculated complex cross-spectra between the hardness and intensity. We multiplied the complex Fourier amplitudes of the intensity, by the complex conjugate of the complex Fourier amplitudes of the hardness (e.g. van der Klis et al. 1987). At each frequency in the resultant cross-spectrum there is a corresponding cross-vector $C$, with a real and imaginary component. The phase of the cross-vector is the phase difference between the variations in hardness and the variations in intensity; a negative

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**Figure 1.** Hardness–intensity diagram of Standard 2 data (16-s averages). The hardness is the counting rate ratio between the 8.7–19.7 keV and 6.2–8.7 keV bands, and the intensity is the counting rate in the range 2.0–19.7 keV. The solid line shows the spline used to calculate $S_i$. A representative error bar is shown.
phase means that hardness lags intensity. A phase of 0° means that hardness and intensity are positively correlated, and a phase of 180° means they are anticorrelated.

We then constructed average complex cross-spectra. At each frequency, we averaged together the real and imaginary components from all cross-spectra for which the corresponding point in the HID was within a specified range of hardness and intensity. The mean amplitude and phase at each frequency was calculated from the mean real and imaginary components. The uncertainties in the mean real and imaginary components are the observed standard deviation in the mean of those components, and we determined the uncertainties in amplitude and phase by using error propagation. The phases at the Nyquist frequency are always either 0° or 180° so they have no error bars.

If, at a particular frequency, the hardness and intensity are uncorrelated, then the phases of the corresponding vector $G$ in the average cross-spectrum will have Gaussian distributions with a mean of zero. The real component of $G$ has a variance, $\sigma_R^2$, that is equal to the variance of the imaginary component, $\sigma_I^2$. These may be calculated by using the expression

$$\sigma_k^2 = \frac{\sigma_R^2 + \mu_R^2}{2M},$$

where $\sigma_R$ and $\mu_R$ are the observed standard deviation and mean, respectively, of the amplitudes of the set of cross-vectors that were averaged together and $M$ is the number of vectors comprising that average.

Therefore, in the absence of a correlation between intensity and hardness, the squared amplitude $|G|^2$ of the average cross-vector is distributed such that the probability of observing a $|G|^2$ greater than a certain threshold level $T$ is given by (Dieters et al. 2000; Dieters, private communication)

$$\text{Prob}(|G|^2 > T) = \exp \left( - \frac{T}{|G_0|^2} \right),$$

where

$$|G_0|^2 = \sigma_k^2 + \sigma_k^2 = 2\sigma_k^2,$$

$$|G_0|^2 = \frac{\sigma_R^2 + \mu_R^2}{M}.$$  (5)

Given an observed squared amplitude $T$, the significance of the detection of a correlation, expressed as a percentage, is given by

$$\text{significance} = 100 \times \left[ 1 - \exp \left( - \frac{T}{|G_0|^2} \right) \right].$$

The cross-vector at the Nyquist frequency has only a real component, so it must be treated separately. The value $|G|^2/\sigma_R^2$ is distributed as $\chi^2$ with one degree of freedom, where $\sigma_R^2 = (\sigma_R^2 + \mu_R^2)/M$.

For a comparison with the analytical significance levels, we also used a Monte Carlo simulation to determine the significance of the observed correlations. We randomized the phase difference between the hardness and intensity at each frequency, in each individual complex cross-spectra, while maintaining the observed amplitudes. We then used those ‘random-phase’ cross-spectra to construct an average cross-spectrum. We repeated this procedure 10 000 times and obtained, at each frequency, the distribution of mean amplitudes that would be present if our data were actually uncorrelated. With this method, the significance of a correlation is equal to the percentage of random-phase amplitudes that are less than the observed amplitude.

We deemed the hardness and intensity to be correlated, at a particular frequency, if the significance obtained from the analytical method was at least 90 per cent. The results obtained from the Monte Carlo method were, on average, within 0.3 per cent significance of those found from the analytical method.

We repeated the entire procedure twice. First, using a time resolution of 8 s with 256-s intervals, corresponding to the frequency range 0.003 906 25–0.0625 Hz, which allowed us to investigate the frequency range in which the power-law component dominates. Secondly, using a time resolution of 0.125 s with 4-s intervals, corresponding to the frequency range 0.25–4.00 Hz, which allowed us to investigate the influence of low-frequency noise and flaring branch noise on our cross-spectra.

3 FAST-TIME VARIABILITY

In Fig. 2 we present representative 0.0625–300 Hz power spectra from the NB (Fig. 2 top; $S_z$ range 1.53–1.85) and FB (Fig. 2 bottom; $S_z$ range 2.03–3.0), and the various components we identified. We detected three features: very low-frequency noise; low-frequency noise/flaring branch noise; and a high-frequency peaked noise component.

![Figure 2](https://example.com/fig2.png)

**Figure 2.** Representative power spectra (2.0–40 keV) from the NB ($S_z$ range 1.53–1.85) and FB ($S_z$ range 2.03–3.0). The white-noise levels have been subtracted and the solid lines show the best-fitting models.
The kilohertz quasi-periodic oscillations were only detected at $S_\nu = 1.66$. In Table 2 we present the best-fitting values of the kHz QPOs in the NB. We investigated the energy dependence of the kHz QPOs by fitting energy-resolved power spectra corresponding to $S_\nu = 1.66$. We fixed the centroid frequencies and FWHM at the values found from the 2.0–40 keV power spectrum. In the energy-resolved spectra, we only detected kHz QPOs in the 5.1–40 keV range, with fractional rms amplitudes of $2.3 \pm 0.2$ and $2.1 \pm 0.2$ per cent for the lower and upper peaks, respectively. In the energy range 2.0–8.7 keV, the upper limits of the rms for the lower and upper peaks were 2.1 and 1.8 per cent, respectively. Therefore, the kHz QPOs in Sco X-2 are hard, like those seen in other objects (e.g. van der Klis 2000 and references therein). Zhang et al. (1998) fitted the kHz QPOs using Gaussians; we also fitted our QPOs using Gaussians and found best-fitting values consistent with their results. The $\chi^2$/degrees of freedom (dof) was 0.97/51 for the Gaussian model, compared with 0.93/51 for the Lorentzian model.

To investigate the energy dependence of the 0.0625–300 Hz power spectral features we used energy-resolved power spectra corresponding to the average spectra shown in Fig. 2. We fixed the centroid frequencies and FWHM at the values found from the 2.0–40 keV spectra. The results are shown in Table 3.

Table 1. Best-fitting values from average power spectra (2.0–40 keV).

<table>
<thead>
<tr>
<th>$S_\nu$</th>
<th>VLFN</th>
<th>LFN/FBN</th>
<th>High-frequency peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Index</td>
<td>rms (per cent)</td>
<td>Freq (Hz)</td>
</tr>
<tr>
<td>1.66 ± 0.04</td>
<td>1.55 ± 0.07</td>
<td>1.40 ± 0.05</td>
<td>5.4 ± 0.2</td>
</tr>
<tr>
<td>1.79 ± 0.04</td>
<td>1.37 ± 0.06</td>
<td>1.33 ± 0.04</td>
<td>7.6 ± 0.2</td>
</tr>
<tr>
<td>1.91 ± 0.04</td>
<td>1.24 ± 0.04</td>
<td>1.32 ± 0.03</td>
<td>7.6 ± 0.2</td>
</tr>
<tr>
<td>2.00 ± 0.02</td>
<td>1.56 ± 0.04</td>
<td>1.83 ± 0.05</td>
<td>5.8 ± 0.1</td>
</tr>
<tr>
<td>2.05 ± 0.01</td>
<td>1.68 ± 0.06</td>
<td>1.99 ± 0.08</td>
<td>5.5 ± 0.1</td>
</tr>
<tr>
<td>2.09 ± 0.01</td>
<td>1.76 ± 0.06</td>
<td>2.20 ± 0.09</td>
<td>5.2 ± 0.1</td>
</tr>
<tr>
<td>2.15 ± 0.02</td>
<td>1.74 ± 0.05</td>
<td>2.35 ± 0.08</td>
<td>5.4 ± 0.1</td>
</tr>
<tr>
<td>2.21 ± 0.01</td>
<td>1.68 ± 0.04</td>
<td>2.41 ± 0.08</td>
<td>5.5 ± 0.1</td>
</tr>
<tr>
<td>2.26 ± 0.02</td>
<td>1.72 ± 0.04</td>
<td>2.78 ± 0.09</td>
<td>4.6 ± 0.3</td>
</tr>
<tr>
<td>2.32 ± 0.02</td>
<td>1.71 ± 0.04</td>
<td>2.99 ± 0.09</td>
<td>4.4 ± 0.6</td>
</tr>
<tr>
<td>2.41 ± 0.03</td>
<td>1.73 ± 0.04</td>
<td>3.23 ± 0.12</td>
<td>3.3 ± 1.5</td>
</tr>
<tr>
<td>2.55 ± 0.05</td>
<td>1.64 ± 0.03</td>
<td>3.09 ± 0.10</td>
<td>3.3°</td>
</tr>
<tr>
<td>2.77 ± 0.09</td>
<td>1.60 ± 0.02</td>
<td>5.45 ± 0.12</td>
<td>3.3°</td>
</tr>
</tbody>
</table>

*Fixed parameter.

In the next three subsections we describe in more detail the properties of the LFN/FBN peak, the high-frequency peak and the VLFN.

3.1 Low-frequency noise/flaring branch noise peak

In Fig. 3 we present the centroid frequency, FWHM, $\nu_{\text{max}}$ and fractional rms amplitude of the LFN/FBN peak (see Fig. 2) as a function of $S_\nu$.

There is an increase in centroid frequency with movement down the NB, while the FWHM, $\nu_{\text{max}}$ and rms are consistent with being constant. The mean $\nu_{\text{max}}$ in the NB was 8.2 ± 0.2 Hz. With movement into the FB the centroid frequency decreases abruptly, and the rms increases sharply. There is no significant change in the FWHM and $\nu_{\text{max}}$. Overall as the source moves up the FB the centroid frequency decreases while the FWHM increases. The $\nu_{\text{max}}$ of the peak decreases as the object moves from $S_\nu = 2.05$ to 2.15, and it then increases with further movement up the FB. We note that $\nu_{\text{max}}$ varies less than the centroid frequency. The rms is strongest at $S_\nu = 2.05$, and decreases until it becomes undetectable in the top half of the FB.

In the NB the peak is strongest in the 6.5–8.7 keV band, and in the FB it is strongest in the highest energy band (Table 3). The overall phenomenology suggests that this peak is LFN in the NB, and then evolves into, or is replaced by, FBN as the source moves into the FB. This interpretation is discussed further in Section 4.1.

3.2 High-frequency peak

3.2.1 High-frequency peak in the normal branch

In the NB, the high-frequency peak (see Fig. 2 top) had a centroid frequency in the range 11–22 Hz, and it exhibited no significant

Table 2. Best-fitting kilohertz QPO values from NB average power spectra (2.0–40 keV).

<table>
<thead>
<tr>
<th>$S_\nu$</th>
<th>Freq (Hz)</th>
<th>Lower kHz QPO FWHM (Hz)</th>
<th>rms (per cent)</th>
<th>Freq (Hz)</th>
<th>Upper kHz QPO FWHM (Hz)</th>
<th>rms (per cent)</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.66 ± 0.04</td>
<td>715 ± 12</td>
<td>98 ± 50</td>
<td>2.0 ± 0.4</td>
<td>985 ± 7</td>
<td>62 ± 31</td>
<td>1.6 ± 0.3</td>
<td>0.93/51</td>
</tr>
<tr>
<td>1.79 ± 0.04</td>
<td>715°</td>
<td>98°</td>
<td>&lt;1.4</td>
<td>985°</td>
<td>62°</td>
<td>&lt;1.1</td>
<td>0.99/57</td>
</tr>
<tr>
<td>1.91 ± 0.04</td>
<td>715°</td>
<td>98°</td>
<td>&lt;1.2</td>
<td>985°</td>
<td>62°</td>
<td>&lt;0.4</td>
<td>1.22/57</td>
</tr>
</tbody>
</table>

*Fixed parameter.
change in its centroid frequency or fractional rms amplitude (see Table 1). There is marginal evidence of a decrease in the FWHM with increasing rank number. In energy-resolved power spectra in the NB we detected the peak only in the 8.7–40 keV band (see Table 3).

In Fig. 4 we present the 2.0–40 keV average power spectrum from the uppermost part of the NB, with $S_r = 1.66$. We used power-density-times-frequency on the vertical axis because this shows the power spectral features more clearly. A two-Lorentzian fit to the power spectrum (Fig. 4 top; Table 1) gave $\chi^2_{\nu}/\nu = 1.37/76$. The probability of exceeding this $\chi^2_{\nu}$ is 0.0178, so the two-Lorentzian fit is formally satisfactory. However, $\chi^2 = 1.37$ is still rather high. Moreover, there is a clear excess of power in the range 45–60 Hz, which is where we would expect to find a horizontal branch oscillation. Therefore, we thought it was worthwhile to explore the option of fitting the NB data using three Lorentzians, even though the addition of another Lorentzian to the model is not statistically justified.

We used a three-Lorentzian model to fit the $S_r = 1.66$ power spectrum and obtained $\chi^2_{\nu}/\nu = 1.16/73$. An F-test indicated a 3.1σ improvement to the fit. The best-fitting three-Lorentzian model is shown in Fig. 4 (bottom). We also fitted the power spectrum corresponding to $S_r = 1.79$ in the same fashion and obtained $\chi^2_{\nu}/\nu = 1.02/73$. An F-test indicated a 3.5σ improvement to the fit. The best-fitting values from both of the three-Lorentzian fits are presented in Table 4.

We also fitted the $S_r = 1.91$ power spectrum with a three-Lorentzian model and obtained $\chi^2_{\nu}/\nu = 1.06/73$. An F-test indicated this to be a 1.4σ improvement. It is not surprising that, in this power spectrum, the three-Lorentzian model was not a significant improvement over the two-Lorentzian model. There is no obvious excess of power in the range 45–60 Hz, in contrast to the excess power seen at $S_r = 1.66$. In Table 4 we show again, for comparison with the values from the three-Lorentzian fits at $S_r = 1.66$ and 1.79, the best-fitting values from a two-Lorentzian fit to the $S_r = 1.91$ power spectrum.

Through comparison with the other Z sources, in particular Sco X-1 and GX 17+2 (e.g. Wijnands & van der Klis 1999 and references therein; Homan et al. 2002), we may identify the three Lorentzians as LFN, a possible sub-HBO and a possible HBO. A detailed comparison is given in Section 4.2.2.

If we assume we have detected three peaked noise features at $S_r = 1.66$ and 1.79, and only two features at $S_r = 1.91$, then, as Sco X-2 moves down the NB, the peak representing the possible HBO disappears, while the possible sub-HBO remains strong (see Table 4). With movement down the NB, the $v_{\text{max}}$ of the possible sub-HBO is consistent with remaining constant.

Even though an F-test indicated that, at $S_r = 1.66$, the three-Lorentzian model was a 3.1σ improvement over the two-Lorentzian model, we stress again that the two-Lorentzian model was formally a satisfactory fit. Therefore, even though we have investigated the use of a three-Lorentzian model, we cannot conclude that we have detected an HBO. Since we have not detected an HBO, we can measure an upper limit by fixing the centroid frequency and FWHM at the values found in, for example, Sco X-1. In that object, the centroid frequency was $\sim 45$ Hz, and the FWHM was in the range $\sim 8−40$ Hz (van der Klis et al. 1997). The 2.0−40 keV upper limits of an HBO at $S_r = 1.66$, with the FWHM fixed at 10, 20, 30 and 40 Hz, were 1.0, 1.6, 1.9 and 2.1 per cent, respectively.

### 3.2.2 High-frequency peak in the flaring branch

We initially fitted the average FB spectrum (2.0–40 keV; see Fig. 2 bottom) with a power law and single Lorentzian, representing very low-frequency noise and flaring branch noise, respectively, which gave $\chi^2_{\nu}/\nu = 1.67/79$. The probability of exceeding that $\chi^2_{\nu}$ is 0.000 17, indicating an unsatisfactory fit at the 99.98 per cent significance level. Therefore, we added a second Lorentzian to the model and obtained $\chi^2_{\nu}/\nu = 1.28/76$. An F-test indicated this to be a 4.1σ improvement to the fit. The best-fitting centroid frequency, FWHM and fractional rms amplitude of the additional peak were $54^{+11}_{−8}$, $96^{+60}_{−53}$ Hz and $1.0^{+0.2}_{−0.1}$ per cent, respectively. The best-fitting two-Lorentzian model is shown as a solid line in Fig. 2 bottom.

We also detected the high-frequency peak in the 5.1–40 keV power spectrum from the FB, with an rms of $1.3 \pm 0.1$ per cent (see Table 3). The non-detection of this feature in the 2.0–8.7 keV band, with an upper limit of 1 per cent, shows that it is genuinely hard.

### 3.3 Very low-frequency noise

Very low-frequency noise was detected in all regions of the Z track. In Fig. 5 we present the power-law index and fractional rms amplitude of the VLFN as a function of $S_r$. The NB/FB vertex seems to be a critical position. The index becomes less steep as the source moves down the NB, and then abruptly becomes steeper again at

---

**Table 3.** Best-fitting values from energy-resolved power spectra from the NB and FB.

<table>
<thead>
<tr>
<th>Energy range (keV)</th>
<th>VLFN</th>
<th>Peaked noise rms (per cent)</th>
<th>$\chi^2_{\nu}/\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Index</td>
<td>LFN/FBN</td>
<td>High freq. peak</td>
</tr>
<tr>
<td>Normal branch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0–40</td>
<td>1.44±0.04</td>
<td>1.35±0.03</td>
<td>2.48±0.17</td>
</tr>
<tr>
<td>2.0–5.1</td>
<td>1.10±0.12</td>
<td>0.85±0.03</td>
<td>2.11±0.07</td>
</tr>
<tr>
<td>5.1–6.5</td>
<td>1.55±0.15</td>
<td>1.41±0.08</td>
<td>3.20±0.08</td>
</tr>
<tr>
<td>6.5–8.7</td>
<td>1.68±0.12</td>
<td>1.74±0.10</td>
<td>3.61±0.07</td>
</tr>
<tr>
<td>8.7–40</td>
<td>1.52±0.06</td>
<td>2.24±0.06</td>
<td>2.74±0.13</td>
</tr>
<tr>
<td>Flaring branch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0–40</td>
<td>1.72±0.02</td>
<td>3.25±0.05</td>
<td>2.98±0.04</td>
</tr>
<tr>
<td>2.0–8.7</td>
<td>1.68±0.02</td>
<td>2.93±0.04</td>
<td>2.83±0.01</td>
</tr>
<tr>
<td>5.1–40</td>
<td>1.73±0.02</td>
<td>3.89±0.06</td>
<td>3.45±0.06</td>
</tr>
<tr>
<td>5.1–6.5</td>
<td>1.66±0.02</td>
<td>2.42±0.04</td>
<td>2.40±0.03</td>
</tr>
<tr>
<td>6.5–8.7</td>
<td>1.69±0.03</td>
<td>3.22±0.06</td>
<td>3.14±0.04</td>
</tr>
<tr>
<td>8.7–40</td>
<td>1.70±0.02</td>
<td>3.74±0.07</td>
<td>3.49±0.03</td>
</tr>
<tr>
<td></td>
<td>1.77±0.02</td>
<td>4.71±0.09</td>
<td>3.78±0.03</td>
</tr>
</tbody>
</table>
the vertex. The index remains roughly constant with movement up the FB until \( S_z \sim 2.5 \), after which it decreases slightly. In the FB, the mean value of the index is 1.70 ± 0.02. The rms is consistent with remaining constant in the NB, and then increases abruptly at the vertex. The VLFN then continues to strengthen with movement up the FB, and is strongest in the highest energy band.

3.3.1 VLFN and motion through the Z track

We constructed an average power spectrum from the rank interval 1.87–1.88, which corresponds to the vertical part of the NB in the HID. In this region of the NB there is no associated change in intensity with motion along the Z track. Therefore, if VLFN is associated purely with movement through the track, then it should be absent in this power spectrum. We found VLFN with a power-law index and rms of 1.1 ± 0.2 and 1.1 ± 0.1 per cent, respectively. These are consistent with the best-fitting values of the VLFN found in other parts of the NB (see Table 1).

The detection of VLFN in the vertical part of the NB suggests that VLFN is not caused solely by movement along the track. However, it is possible that within each stretch of data over which Fourier transforms were calculated, the source moves a substantial distance away from the vertical region of the NB, by moving up and down the NB, or even into the FB, and thereby producing associated changes in intensity. In Fig. 6 (top), we present the HID constructed from 32-s averages of single-bit and event-mode data. In Fig. 6 (bottom)
**Table 4.** Best-fitting values from the three-Lorentzian fits to the $S_z = 1.66$ and 1.79 power spectra, and the two-Lorentzian fit to the $S_z = 1.91$ power spectrum (2.0–40 keV).

<table>
<thead>
<tr>
<th>$S_z$</th>
<th>Freq (Hz)</th>
<th>FWHM (Hz)</th>
<th>$v_{\text{max}}$ (Hz)</th>
<th>rms (per cent)</th>
<th>Freq (Hz)</th>
<th>FWHM (Hz)</th>
<th>$v_{\text{max}}$ (Hz)</th>
<th>rms (per cent)</th>
<th>Freq (Hz)</th>
<th>FWHM (Hz)</th>
<th>$v_{\text{max}}$ (Hz)</th>
<th>rms (per cent)</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.66 ± 0.04</td>
<td>5.1 ± 0.3</td>
<td>8.2 ± 2</td>
<td>6.5 ± 0.7</td>
<td>2.2 ± 0.4</td>
<td>13 ± 5</td>
<td>29 ± 10</td>
<td>19 ± 5</td>
<td>2.3 ± 0.7</td>
<td>48 ± 2</td>
<td>26 ± 8</td>
<td>50 ± 2</td>
<td>1.5 ± 0.3</td>
<td>1.16/73</td>
</tr>
<tr>
<td>1.79 ± 0.04</td>
<td>7.3 ± 0.2</td>
<td>7.1 ± 0.8</td>
<td>8.1 ± 0.3</td>
<td>2.4 ± 0.2</td>
<td>16 ± 2</td>
<td>16 ± 6</td>
<td>18 ± 2</td>
<td>1.9 ± 0.5</td>
<td>46 ± 10</td>
<td>59 ± 17</td>
<td>55 ± 10</td>
<td>2.1 ± 0.4</td>
<td>1.02/73</td>
</tr>
<tr>
<td>1.91 ± 0.04</td>
<td>7.6 ± 0.2</td>
<td>8.0 ± 1.3</td>
<td>8.6 ± 0.4</td>
<td>2.1 ± 0.2</td>
<td>14 ± 4</td>
<td>32 ± 6</td>
<td>21 ± 3</td>
<td>2.4 ± 0.3</td>
<td>46$^a$</td>
<td>59$^a$</td>
<td>55$^a$</td>
<td>&lt;1.5</td>
<td>1.09/76</td>
</tr>
</tbody>
</table>

$^a$Fixed parameter.

---

**Figure 5.** VLFN index and fractional rms amplitude as a function of rank number (2.0–40 keV).

---

we have plotted, in a HID, all of the data points in the vertical part of the NB (hardness interval 1.03–1.08; see Fig. 6 top) using a time resolution of 1 s. If there were substantial movement up and down the NB within each 32-s interval, then we would expect the 1-s points to exhibit an arc-like distribution, reflecting the shape of the NB. We observed a vertical distribution, suggesting that the changes in intensity comprising the VLFN are not caused purely to movement along the Z track. However, we caution that the error bars are large.

A more sensitive way of investigating the correlation between hardness and intensity is to use cross-spectra (see Section 2.3). With phase measurements, we can determine whether the variability at a particular frequency is not entirely owing to movement along the Z track. In the FB and the upper part of the NB, where the track exhibits an increase in hardness with increasing intensity (see Fig. 6), movement along the track must produce a phase of $0^\circ$. In the lower part of the NB, where the branch exhibits a decrease in hardness with increasing intensity, movement along the track must produce a phase of $180^\circ$.

In Table 5, we present the phases from the 256-, 32- and 4-s intervals. We only show phases for the frequencies at which there was a detection of a correlation between hardness and intensity at the 90 per cent confidence level. The upper NB corresponds to data with hardness $>1.06$, and the lower NB to data in the hardness range 1.0–1.06. For the FB, we used data with intensity $>9000$ count s$^{-1}$. We also present the significance of the detection of the correlation at each frequency, as measured from both the analytical and Monte Carlo method, and rounded to the nearest one-hundredth of a per
cent. Note that >3σ detections were generally only obtained in the FB.

Since we wish to investigate VLFN, we need to determine the frequencies at which VLFN is the primary influence on the phases. Above ~2 Hz the variations in intensity are dominated by LFN/FBN, which is stronger than the VLFN at those frequencies; at lower frequencies the effects of LFN/FBN may still be present. At frequencies where LFN/FBN dominates, the phases are characterized by non-zero values (see Table 5); however, we cannot, of course, assume that every observation of a non-zero phase is a result of LFN/FBN.

If we observe, at a particular frequency, a phase that is consistent with zero, then we can conclude that the phases observed at that frequency may be caused by either VLFN or LFN/FBN. Any non-zero phases with being zero, then we can conclude that the phases observed at that frequency may be caused by either VLFN or LFN/FBN.

Table 5. Phases from average cross-spectra from the upper NB, lower NB and FB.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Upper NB</th>
<th>Lower NB</th>
<th>FB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.003 906 25</td>
<td>6 ± 7</td>
<td>174 ± 19</td>
<td>(94.56/94.80)</td>
</tr>
<tr>
<td>0.007 8125</td>
<td>8 ± 15</td>
<td>-3 ± 3</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.011 718 75</td>
<td>-9 ± 16</td>
<td>-2 ± 3</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.015 625</td>
<td>-26 ± 14</td>
<td>-4 ± 3</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.019 531 25</td>
<td>-33 ± 18</td>
<td>-1 ± 4</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.023 4375</td>
<td>27 ± 16</td>
<td>0 ± 5</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.027 343 75</td>
<td>6 ± 29</td>
<td>-3 ± 6</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.031 25°</td>
<td>38 ± 25</td>
<td>9 ± 7</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.031 25°</td>
<td>20 ± 8</td>
<td>-2 ± 8</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.035 156 25</td>
<td>-25 ± 17</td>
<td>-2 ± 8</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.039 0625</td>
<td>-25 ± 17</td>
<td>-12 ± 8</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.042 968 75</td>
<td>-25 ± 17</td>
<td>8 ± 9</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.046 875</td>
<td>-25 ± 17</td>
<td>-13 ± 8</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.050 781 25</td>
<td>-25 ± 17</td>
<td>-4 ± 8</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.054 6875</td>
<td>21 ± 21</td>
<td>3 ± 9</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.058 593 75</td>
<td>-25 ± 17</td>
<td>3 ± 8</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.0625°</td>
<td>-25 ± 17</td>
<td>0</td>
<td>(99.94/99.98)</td>
</tr>
<tr>
<td>0.0625°</td>
<td>12 ± 13</td>
<td>-7 ± 4</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.093 75</td>
<td>0 ± 19</td>
<td>-8 ± 20</td>
<td>(97.70/97.78)</td>
</tr>
<tr>
<td>0.125</td>
<td>-16 ± 20</td>
<td>-12 ± 6</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.156 25</td>
<td>-53 ± 20</td>
<td>-13 ± 10</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.1875</td>
<td>-176 ± 24</td>
<td>-13 ± 12</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.218 75</td>
<td>-15 ± 18</td>
<td>15 ± 18</td>
<td>(99.56/99.59)</td>
</tr>
<tr>
<td>0.25°</td>
<td>-25 ± 22</td>
<td>-5 ± 12</td>
<td>(100/100)</td>
</tr>
<tr>
<td>0.281 25</td>
<td>-24 ± 26</td>
<td>(91.46/90.99)</td>
<td></td>
</tr>
<tr>
<td>0.3125</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.343 75</td>
<td>-15 ± 23</td>
<td>(96.38/96.06)</td>
<td></td>
</tr>
<tr>
<td>0.375</td>
<td>-</td>
<td>-177 ± 28</td>
<td>(90.56/97.73)</td>
</tr>
<tr>
<td>0.4062</td>
<td>-</td>
<td>28 ± 20</td>
<td>(98.03/97.82)</td>
</tr>
<tr>
<td>0.4375</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.468 75</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.5°</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.5°</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.75</td>
<td>102 ± 16</td>
<td>(99.78/99.76)</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.25</td>
<td>-</td>
<td>35 ± 26</td>
<td>(90.59/90.29)</td>
</tr>
<tr>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.75</td>
<td>-162 ± 20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.0</td>
<td>-178 ± 25</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.5</td>
<td>-167 ± 24</td>
<td>(94.48/94.44)</td>
<td></td>
</tr>
<tr>
<td>2.75</td>
<td>74 ± 23</td>
<td>(95.63/95.29)</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>80 ± 25</td>
<td>(92.61/92.55)</td>
<td></td>
</tr>
<tr>
<td>3.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3.75</td>
<td>-131 ± 18</td>
<td>(99.19/99.33)</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

°256-s intervals.
\[\text{°}32-s intervals.
\[\text{°}4-s intervals.
and, there are non-zero phases at frequencies in the range 0.1875–3.75 Hz. We shall, therefore, use 0.1875 Hz as our very rough estimate of the lowest frequency at which the phases are primarily influenced by LFN/FBN and thereby conservatively restrict our study of VLFN to frequencies less than 0.1875 Hz.

In the FB and upper NB, the phases are consistent with being 0°, indicating that the variations in intensity may be a result entirely of movement along the Z track. We combined the 256-s interval FB data into a single frequency bin, with a mean frequency of \( \pm 0.033 \) Hz, and measured a phase of \(-3.1 \pm 1.4\), which is also consistent with zero.

In the lower NB, the phase at \( \pm 0.004 \) Hz is consistent with being 180°; therefore, at this frequency, the intensity and hardness are negatively correlated. In the frequency range \( \pm 0.016–0.094 \) Hz, the phases are consistent with being 0°; therefore, in this frequency range, the intensity and hardness are positively correlated. Since the Z track in the lower NB exhibits a negative correlation between hardness and intensity, the movement giving rise to the variations in intensity in the range \( \pm 0.016–0.094 \) Hz must have a cross-track component. And, since we observed a negative correlation between intensity and hardness at \( \pm 0.004 \) Hz, the cross-track component must become more prominent at higher frequencies.

It is important to note again the limitations of our measurements. Only about half of our detections are at the >3σ level. This is particularly a problem in the lower NB, where we have only \( \sim 15 \) ks of data.

### 4 DISCUSSION

Using Zhang et al.’s (1998) RXTE data, we have carried out the most comprehensive investigation of the X-ray fast-time variability of Sco X-2 thus far, as a function of position on the Z track. Our primary discoveries are: the properties of the low-frequency noise/flaring branch noise peak, and the very low-frequency noise, exhibit abrupt changes with movement from the NB into the FB; there is a peaked noise feature with a centroid frequency in the range 11–54 Hz, which, in the NB, may contain either one or two components; and, very low-frequency noise is not entirely a result of motion along the Z track.

#### 4.1 Low-frequency noise and flaring branch noise

The peak we observed in the NB and FB, with a centroid frequency in the range 3.3–7.6 Hz, is not an N/FBO: NBOs are much narrower than the peak we observed; the centroid frequency of an FBO increases rapidly with movement up the FB, in contrast to our peak; and FBOs are only present in the lowest 10–20 per cent of the FB, while the feature in Sco X-2 is present until about halfway up the branch (see also Section 1.2). Given the presence of kHz QPOs in the upper NB, and the fact that the peak has a \( v_{\text{max}} \) in the range 7.5–9.1 Hz, which is consistent with the LFN found in other Z sources (e.g. GX 17+2, Homan et al. 2002; Sco X-1, Dieters & van der Klis 2000), we argue that we have detected LFN in the NB. In the FB, the peak is similar to the FBN found earlier in Sco X-2 (e.g. Agrawal & Bhattacharyya 2001 and references therein), and we identify it as such.

LFN is a hard phenomenon (e.g. van der Klis 1995a). For example, Jonker et al. (2000) found that the fractional rms amplitude of the LFN in GX 340+0 was more than a factor of 3 greater in the 13–60 keV band than it was in the 2–5 keV band. In contrast, the LFN we observed is strongest in the 6.5–8.7 keV band. This difference suggests that maybe we have not observed LFN, since different production mechanisms give rise to different energy dependences [e.g. compare HBOs with NBOs, see van der Klis (1995a) and references therein]. However, the fractional rms amplitude spectrum of NBOs, for example, is known to differ between objects (e.g. van der Klis 1995a and references therein; Dieters & van der Klis 2000; Dieters et al. 2000) and LFN may similarly behave differently per source. This suggestion can be confirmed through a sensitive investigation of the \( S \) dependence of the LFN that we detected, and by making a comparison with other Z sources.

In previous observations of Sco X-2 the properties of the peaked noise in the NB was found to be similar to that seen in the FB, suggesting that it was the same feature in both branches (Agrawal & Bhattacharyya 2001). We argue, for two reasons, that FBN is different from LFN: the properties of the LFN/FBN peak, as seen in Fig. 3, exhibit abrupt changes at the NB/FB vertex; and the energy dependence of the peak differs between NB and FB. We note that according to the ‘unified model’ (Psaltis, Lamb & Miller 1995), the inferred mass-accretion rates are expected to be sub-Eddington in the NB, and super-Eddington in the FB, suggesting that the mechanism producing the variability in the NB may be different from that in the FB. However, the properties of the N/FBO, for example, also differ between NB and FB, with the changes occurring near the vertex (e.g. Dieters & van der Klis 2000), and the NBO and FBO are still thought to be related. Likewise, there remains the possibility that LFN evolves into FBN.

Our observations of FBN support the conclusions reached by O’Neill et al. (2001a), which were detailed in Section 1.2. In particular, we note again the similarity between FBN and the broad peak seen in the FB of Cyg X-2 at low overall intensities (Kuulkers, Wijnands & van der Klis 1999; see also Agrawal & Bhattacharyya 2001; O’Neill et al. 2001a). The feature in Cyg X-2 was fitted with a cut-off power law, with a \( v_{\text{max}} \) of \( 10 \pm 3 \) Hz. This is consistent with the LFN we observed. The peak in Cyg X-2 was not observed in the NB, with a fractional rms amplitude upper limit of 1.0 per cent, compared with the FB rms of 2.7 ± 0.2 per cent. An investigation of the \( S \) dependence of the Cyg X-2 peak will reveal whether or not it is the same phenomenon as FBN. Furthermore, a stringent upper limit on the rms of the peak in the NB would support our suggestion that FBN is not the same as LFN.

We now compare the LFN and FBN we observed in Sco X-2, with the LFN observed in the NB and FB of GX 17+2 (Homan et al. 2002). The \( v_{\text{max}} \) of the LFN in the NB of Sco X-2 is generally a few hertz lower than that seen in the NB of GX 17+2, and it is consistent with the \( v_{\text{max}} \) observed in the NB. There is no abrupt decrease in the centroid frequency and increase in the fractional rms amplitude of the LFN in GX 17+2, with movement from the NB into the FB, suggesting that it may not be the same as Sco X-2 LFN/FBN. However, Homan et al. (2002) stated that their best-fitting values of LFN in the lower NB and lower FB were probably influenced by the N/FBO that was present, so the true LFN phenomenology may have been masked. The overall behaviour of \( v_{\text{max}} \) in the FB is similar in both objects, and the decrease in the fractional rms amplitude of the LFN in GX 17+2, with movement up the FB, is remarkably similar to FBN. In contrast to the FBN we observed, the LFN in GX 17+2 was detected as high as about 85 per cent of the way up the FB. However, we note again that Agrawal & Bhattacharyya (2001) reported the detection of peaked noise in the FB of Sco X-2 at about 80 per cent of the way up the FB.

In addition to GX 17+2, a close examination of the LFN in Sco X-1 is also desirable. Sco X-1 has been observed by RXTE, with 2–60 keV counting rates of \( \sim 10^6 \) count s\(^{-1}\), and these data are currently
available in the archive (e.g. Yu, van der Klis & Jonker 2001). Of course, more data on Sco X-2 are also required before sufficiently detailed comparisons can be made.

4.2 High-frequency peak in the normal branch

In the NB, we detected a high-frequency peaked noise feature, with a centroid frequency in the range 11–22 Hz. This feature contains power at frequencies where we would expect to find high-frequency noise, a horizontal branch oscillation, and/or a subhorizontal branch oscillation (see Section 1.1). We showed that the NB power spectrum could be fitted satisfactorily with a two-Lorentzian model, using one Lorentzian for the low-frequency noise, and one for the high-frequency peak (see Section 3.2). However, at $S_i = 1.66$, there is an excess of power in the frequency range where we would expect to find an HBO (see Fig. 4). The addition of a third Lorentzian component significantly improved the fit. Therefore, we shall consider both two- and three-Lorentzian models for fitting the NB data.

4.2.1 Two-Lorentzian model for normal-branch data

The high-frequency peak, if considered as a single Lorentzian, resembles Z source HBO. The $v_{\text{max}}$ we found is consistent with that seen in other Z sources (e.g. Hasinger & van der Klis 1989), and it was stronger at higher energies, which is typical of HBO (e.g. Dieters & van der Klis 2000). However, there is some doubt as to the origin of HBO: it may be an instrumental effect from EXOSAT (Berger & van der Klis 1994). Homan et al. (2002) did not detect HBO in a large RXTE data set on GX 17+2, in contrast to previous observations made by EXOSAT. They suggested that in the HB in the EXOSAT observations, where the HBO was too strong to be an instrumental effect, the feature being fitted in power spectra may have actually been the sub-HBO peak.

Is then the high-frequency peak, taken as a single Lorentzian, a sub-HBO peak? At the top of the observed NB, the LFN we detected had a $v_{\text{max}}$ of $7.5 \pm 0.5$ Hz. The centroid frequency, FWHM and $v_{\text{max}}$ of the high-frequency peak were $22 \pm 11$, $70 \pm 11$ and $41 \pm 7$ Hz, respectively. In comparison, when the LFN in GX 17+2 had a $v_{\text{max}}$ of $\sim 7.5$ Hz, its sub-HBO peak had a centroid frequency, FWHM and $v_{\text{max}}$ of $25.2 \pm 1.3$, $21 \pm 7$ and $27 \pm 2$ Hz, respectively, (Homan et al. 2002). The high-frequency peak in Sco X-2 is at the expected centroid frequency of a sub-HBO, but there are some marked differences: we would expect to clearly detect an HBO when a sub-HBO peak is present; the high-frequency peak is much broader than a typical sub-HBO, which results in a much higher $v_{\text{max}}$; and, with movement down the NB, the $v_{\text{max}}$ of the high-frequency peak in Sco X-2 decreased to $21 \pm 3$, while in GX 17+2 the $v_{\text{max}}$ of the sub-HBO peak increased to a maximum of $\sim 50$ Hz. Therefore, we conclude that the high-frequency peak, if considered as a single Lorentzian, cannot be identified as a typical manifestation of a sub-HBO.

4.2.2 Three-Lorentzian model for normal-branch data

We now consider the possibility that the high-frequency peak consists of two Lorentzian features. At $S_i = 1.66$, the peak could be fitted using two Lorentzians, representing a possible sub-HBO and HBO. In the same part of the NB, the lower kHz QPO is at $715 \pm 12$ Hz.

We find that, according to the correlation found by Wijnands & van der Klis (1999), and in comparison to GX 17+2 (Homan et al. 2002), the frequencies of the LFN and possible sub-HBO peak we observed in Sco X-2 are consistent with expectations, assuming the presence of an HBO at 48 Hz.

According to the correlation found by Psaltis et al. (1999a), when the lower kHz QPO is at 715 Hz the HBO is inferred to have a centroid frequency of about 60 Hz. This is somewhat higher than the 48-Hz centroid frequency of our possible HBO. An HBO centroid frequency of 48 Hz corresponds to a lower kHz QPO frequency of about 600 Hz (Psaltis et al. 1999a; Homan et al. 2002). The HBO in Sco X-1 has only been detected with centroid frequencies in the range $\sim 40$–50 Hz, and Sco X-1 also lies off the correlation of Psaltis et al. (1999a); for example, its HBO was found at $\sim 45$ Hz, even when the lower kHz QPOs was at $\sim 875$ Hz (van der Klis et al. 1997). Therefore, we speculate that Sco X-2 is similar to Sco X-1 in this regard, and predict that future observations may reveal an HBO in the same frequency range as seen in Sco X-1.

There remains a problem, however, with the interpretation of our $v_{\text{max}} \sim 20$ Hz feature as being a Z source sub-HBO. If we assume we have detected an HBO and sub-HBO in the NB power spectra at $S_i = 1.66$ and 1.79, then, as Sco X-2 moves down the NB, the sub-HBO peak should disappear before the HBO does. This effect is clearly seen in GX 17+2, in which the sub-HBO peak becomes undetectable in the middle part of the NB while the HBO is present all the way down to the FB (Homan et al. 2002). In contrast, we find that our possible HBO component disappears by $S_i = 1.91$, while the possible sub-HBO component remains strong. Furthermore, the $v_{\text{max}}$ and centroid frequency of the possible sub-HBO at $S_i = 1.79$ and 1.91, are significantly lower than the maximum values observed in the NB in GX 17+2 (Homan et al. 2002). However, we note that the uncertainties on our measurements do allow for an increase in the possible sub-HBO centroid frequency and $v_{\text{max}}$. Therefore, although problematic, we cannot rule out the possibility that we have observed a manifestation of a sub-HBO slightly different from that seen in GX 17+2.

In summary, if three Lorentzians are required to fit the power spectrum from the upper NB, we conclude that the frequency of the lower kHz QPO, relative to the centroid frequency of the HBO, is similar to that seen in Sco X-1 (van der Klis et al. 1997); and the feature with $v_{\text{max}} \sim 20$ Hz may be a sub-HBO peak, though it must be a different manifestation to that seen in GX 17+2.

4.3 Comparison with models

Since flaring branch noise is present at super-Eddington inferred mass-accretion rates, where the accreting material and outgoing radiation must be separated (e.g. Lamb 1991), an adaptation of the photon bubble model (Klein et al. 1996a) may prove useful in explaining it. The photon bubble model was originally applied to X-ray pulsars, in which locally super-Eddington accretion takes place on to the polar caps of a strongly magnetized neutron star (Klein et al. 1996a). Photon bubbles are formed in the settling mound below the accretion shock. The bubbles coalesce to form larger bubbles, and then rise up and lose their photons through diffusion into the accretion shock. The result is quasi-periodic variability in the X-ray intensity, the frequency of which is primarily dependent upon the time it takes for the bubbles to coalesce. Modelling showed that QPOs could be produced at frequencies from as low as 20 Hz to as high as 12 000 Hz, along with a simultaneous power-law component (Klein et al. 1996a,b). It would be interesting to see whether or not a similar process, operating in either a radial inflow or in the accretion funnel on to the neutron star magnetic poles, could give rise to FBN.
In the magnetospheric beat frequency model for horizontal branch oscillations (e.g. Alpar & Shaham 1985; Lamb et al. 1985; Shibazaki & Lamb 1987), the HBO is predicted to be accompanied by a noise component at lower frequencies, with both features expected to be hard. In the power spectra of Z sources it is possible to identify either the LFN or the sub-HBO peak as the noise component (e.g. Wijnands & van der Klis 1999). The LFN that we observed in the NB was strongest at intermediate energies, suggesting that, in the context of the magnetospheric beat frequency model, either LFN is not related to the HBO, or the feature we observed is not classical LFN. We have argued in Section 4.1 that we have observed Z source LFN. If we are correct, then the sub-HBO peak, rather than LFN, might be identified as the noise component that is expected to accompany the HBO.

In the relativistic precession model, the upper and lower kHz QPOs, and the HBO, are all produced by the same blob orbiting in the accretion disc (Stella & Vietri 1998, 1999; Stella, Vietri & Morsink 1999). The model makes clear predictions of the correlations between those frequencies. Unfortunately, since we did not definitely detect an HBO, and the kHz QPOs were only detected in one part of the Z track, we cannot test those predictions. And, our HBO upper limits are too high to draw any meaningful conclusion concerning its presence or otherwise, since weaker HBOs have been observed (e.g. in Sco X-1; van der Klis et al. 1997). If we assume that we have detected an HBO at 48 Hz, with kHz QPOs at 715 and 985 Hz, then the mass and spin frequency of the neutron star can be inferred from the model. Judging from Fig. 1 in Stella & Vietri (1999), the inferred mass is ~2 M⊙; the other Z sources have inferred masses in the range ~1.8–2.2 M⊙ (Stella & Vietri 1999). The mass of the neutron star in Cyg X-2 has been dynamically established as 1.78 ± 0.23 M⊙, which is consistent with the inferred masses (Orosz & Kuulkers 1999). Judging from Fig. 1(b) in Stella et al. (1999), the inferred spin frequency, for neutron star equation of state AU and an assumed mass of 1.95 M⊙, is ~600 Hz; the other Z sources have an inferred spin frequency in the range ~600–900 Hz (Stella et al. 1999).

In the so-called transition layer model (e.g. Titarchuk et al. 1999), Z source LFN is the same phenomenon as atoll source HFN, and the sub-HBO peak is the same phenomenon as atoll source 1–67 Hz QPOs. Both of these phenomena are caused by oscillations in the transition layer between the disc and the neutron star. The HBO, the HBO second harmonic and the upper kHz QPO, are frequencies at which a blob oscillates, having been thrown out of the transition layer into the magnetosphere. The lower kHz QPO is the orbital frequency at the inner edge of the disc. Recently, Wu (2001) found good agreement between the predictions of the model and observations of Z sources and atoll sources. It is unclear how the fractional rms amplitude of LFN is predicted to vary with energy because the actual mechanism that produces that variability has not been specified (Titarchuk & Osherovich 1999). Naturally any such mechanism that is proposed must account for the energy dependence we observed in Sco X-2. If the transition layer model is correct, we can measure the angle δ between the plane of the accretion disc and the equator of the magnetosphere (e.g. Titarchuk et al. 1999). If we assume an HBO frequency of 48 Hz, and use our observed kHz QPO frequencies, then we infer δ = 5.6 ± 0.3, which is within the 5.4–6.0 range found from the other Z sources (Wu 2001).

The sub-HBO seen in Z sources may be interpreted as the fundamental QPO frequency, with the HBO and its second harmonic being interpreted as the second and fourth harmonics of the sub-HBO (Jonker et al. 2000). Jonker et al. (2002) (also Jonker 2001) found a broad feature in GX 5–1 at 1.5 times the HBO frequency, making it the third harmonic of the sub-HBO. They suggested that a warped disc with a twofold symmetry can provide a mechanism that produces odd harmonics that are broader than the even harmonics, and that this mechanism could be used as part of the relativistic precession model. The FWHM of the possible sub-HBO and HBO we observed at Si = 1.66 were 29 ± 10 and 26 ± 8 Hz, respectively. The uncertainties here are too large to test the warped disc model.

4.4 Very low-frequency noise

4.4.1 The importance of studying VLFN

If VLFN is caused by changes in intensity that are associated with the movement of a source along its Z track, then a model for VLFN will provide at least part of the mechanism that gives rise to the Z track.

For example, in the unified model (e.g. Psaltis et al. 1995) the movement along the Z track is driven by changes in the mass-accretion rate that alter the physical conditions in the region of the neutron star and the inner accretion disc. The mass-accretion rate changes from sub- to super-Eddington with movement from the NB into the FB. In this particular context, a model for VLFN will provide the mechanism that produces those changes in the accretion rate.

Recently, van der Klis (2001) suggested that position along the Z track may not be related to the actual mass-accretion rate. Rather, he proposed that rank number is related to the ratio η between the instantaneous accretion rate through the disc, and the long-term average of that rate. In this model, movement to a higher Si requires either an increase in the accretion rate or for the accretion rate to remain constant immediately following a decrease. Conversely, movement to a lower Si occurs either when the accretion rate decreases or when it remains constant immediately following an increase. Again, if VLFN is caused by movement along the track, then the details of this model must be such that η exhibits a power-law variability.

Furthermore, the abrupt changes we observed in the properties of the VLFN with movement through the NB/FB vertex suggests that any model for VLFN should also provide information concerning the physical basis of that transition.

4.4.2 Observations of VLFN

We observed an increase in the fractional rms amplitude of the VLFN with increasing Si, and it was stronger at higher energies. The same behaviour was seen in the Ginga observations of Sco X-2 (O’Neill et al. 2001a), and also in Sco X-1 (Dieters & van der Klis 2000). However, our results are very different from those of the 1998 September and October RXTE data on Sco X-2, in which the VLFN behaved somewhat erratically, and was, on average, stronger in the NB than in the FB (Agrawal & Bhattacharyya 2001). Homan et al. (2002) found that, in GX 17+2, the rms of the VLFN did not increase smoothly with movement up the FB; as the object moved away from the NB/FB vertex, the rms decreased at first, reaching a local minimum at about one-quarter of the way up the FB, and then increased smoothly with increasing Si. However, the VLFN in GX 17+2 was still, on average, stronger in the FB than in the NB. The reason for the differences between our results and those from the 1998 September and October data is unclear. Agrawal & Bhattacharyya (2001) used 8-s intervals when calculating their power spectra, which meant their lowest frequency was 0.125 Hz, compared with 0.0625 Hz in our spectra; this may have produced some differences between the two sets of results owing to interference, during the fitting process, from the peaked noise.
The power-law index of the VLFN we observed decreased with movement down the NB, abruptly increased at the NB/FB vertex, and then remained roughly constant with movement up the FB, decreasing slightly in the upper part of the FB; in the FB, the mean value of the index was 1.70 ± 0.02. In contrast to this, the index of the VLFN found in the 1998 September and October RXTE data exhibited no dependence on $S_z$; in the FB the index had a mean value of 1.64 ± 0.07 (Agrawal & Bhattacharya 2001). In Sco X-1, the power-law index increased with movement down the NB, from 1.2 to 1.7, although, similar to our results, was constant in the FB, with a mean of 1.76 ± 0.04 (Dieters & van der Klis 2000). In GX 17+2, the index gradually increased with movement down the NB and reached a maximum at about 10 per cent of the way up the FB; it then decreased gradually with further movement up the FB (Homan et al. 2002). Of note, however, is that the power-law index in GX 17+2 reached a local maximum of ≈1.6, at roughly three-quarters of the way down the NB, and it then subsequently decreased to reach a local minimum, of ≈0.8, near the NB/FB vertex (see fig. 11 in Homan et al. 2002). A similar effect has also been seen in GX 5−1 (Jonker et al. 2002), and we may have observed the same thing in Sco X-2, albeit with a much broader local minimum.

As discussed in the previous section, understanding VLFN is important in understanding the overall behaviour of Z sources. Therefore, the presence of vastly different VLFN phenomenologies in Sco X-2, during different observations, is an important result that needs to be clarified. Wijnands et al. (1997) found that, in Cyg X-2, the properties of the VLFN varied as the overall intensity level changed; variations in other components of the fast-time variability, and in the X-ray spectral properties, also accompanied those changes. The differences in the VLFN phenomenology in Sco X-2 may be related to the same effect.

4.4.3 VLFN and movement through the Z track

Dieters & van der Klis (2000) identified VLFN in Sco X-1 with movement along the Z track, while Homan et al. (2002) found that, in GX 17+2, the speed of movement through the Z track was not correlated with VLFN strength in all parts of the track. Wijnands et al. (1997) similarly investigated the VLFN in Cyg X-2 at different overall intensities. They found that the speed of movement through the track was highest at the highest overall intensity level, while the VLFN was strongest at the second highest intensity level; they, therefore, concluded that the VLFN in the NB could not solely be caused by movement along the Z track.

We detected VLFN in the vertical part of the NB. Therefore, if VLFN is produced solely by intensity changes that are associated with movement along the track, then, within each interval, there must be significant movement along the track to regions above and below the vertical part of the NB, such that there are variations in intensity. The absence of an arc-like distribution of the 1-s time resolution points suggests that there is no such movement. The 1-s time-domain data points have very large uncertainties in hardness, so we used cross-spectral analysis to investigate the relationship between intensity and hardness.

In the FB and upper NB the variations in the intensity and hardness are consistent with being in phase with each other. This is consistent with the variations in intensity being just a result of movement along the Z track, though it does not rule out a cross-track component.

In the lower NB, we found that at ≈0.004 Hz the variations in intensity were negatively correlated with the variations in hardness, which is consistent with those variations also being caused by movement up and down that part of the NB. However, at higher frequencies, we found that the intensity was positively correlated with hardness, indicating that, at those frequencies, the variations in intensity must be associated with movement that is not directly along the Z track. And, the negative correlation at ≈0.004 Hz suggests that the cross-track component of motion is more prominent at higher frequencies. We caution, however, that these conclusions must remain tentative owing to the low significance, and large uncertainties, of our phase measurements.

4.4.4 Models for VLFN

A model has been proposed to explain power-law variability in black hole candidates (e.g. Mineshige, Takeuchi & Nishimori 1994). Their model can produce power-law fluctuations in the mass-accretion rate from the inner accretion disc, even when the rate of mass injection into the inner part of the disc is random. The predicted X-ray power spectrum exhibits a power-law index of about 1.6, with a flattening at low frequencies. This model can possibly be applied to the unified model, thereby providing the mechanism to produce changes in the accretion rate. Whether or not it can produce a large enough range in mass-accretion rate (0.7–1.02 times the Eddington limit; Psaltis et al. 1995) and a low enough break frequency (Sco X-1 is predicted to have a turnover time-scale of several days; Dieters & van der Klis 2000) needs to be tested.

An alternative, yet similar, model for VLFN is the ‘dripping handrail’ model (e.g. Young & Scargle 1996), in which the amount of matter present at the inner edge of the accretion disc varies both quasi- and aperiodically. If luminosity is considered to be proportional to the mass at the inner edge of the disc, then both a power-law variability and a QPO are produced. The frequency of the QPO is proportional to the accretion rate, so it cannot be identified as flaring branch noise (see also Dieters & van der Klis 2000). If the rate at which matter leaves the disc is considered, then the power-law component disappears (Steiman-Cameron et al. 1994). This model cannot, therefore, produce a power-law variability in mass-accretion rate, and so it cannot be applied to the unified model.

Time-dependent nuclear burning on the surface of the neutron star has also been proposed to produce VLFN, with the power-law index expected to increase with increasing mass-accretion rate (Bildsten 1995). Dieters & van der Klis (2000) noted that the predicted variability has a characteristic time-scale, in contrast to the observed VLFN in Sco X-1, which is a power law over time-scales ranging from 10 s to about 14 h; and the energy available from nuclear burning is not sufficient to produce the observed fractional rms amplitude. Therefore, it is difficult for nuclear burning alone to account for VLFN.

Our results provide further evidence that the variations in intensity comprising the very low-frequency noise are associated with movement that is not directly along the Z track. A possible scenario is that changes in mass-accretion rate, or $\eta$, produce motion in which there is a component both along, and across, the track, and that the cross-track component is more prominent at higher frequencies. Alternatively, changes in mass-accretion rate or $\eta$ might only produce movement along the track, with nuclear burning providing a cross-track component. Except for the transition from the NB into the FB, we observed a general decrease in power-law index with increasing inferred mass-accretion rate. In contrast, the nuclear burning model predicts an increase in index with increasing mass-accretion rate. Therefore, if nuclear burning is found to be contributing significantly to VLFN, the ‘$\eta$ model’ for the Z-track is preferred, since it does not specify a particular mass-accretion rate for each part of the track. As pointed out by Dieters & van der Klis (2000), the two
types of variations would need to combine and produce the observed VLFN power law.

5 CONCLUSIONS

We have carried out the most comprehensive study to date, of the X-ray fast-time variability of Sco X-2 as a function of position on the Z track. We found low-frequency noise in the NB, and typical Sco X-2 flaring branch noise in the FB, with centroid frequencies in the range 3.3–5.8 and 5.4–7.6 Hz, respectively. The LFN was strongest at intermediate photon energies, while FBN was hard. The various models seeking to provide an explanation for LFN in Z sources must account for the energy dependence we observed. With regard to FBN, we confirm the conclusions reached by O’Neill et al. (2001a), and again note the similarity between FBN and the peaked noise seen the FB of Cyg X-2 at low overall intensities (Kuulkers et al. 1999). We suggest that an adaptation of the photon bubble model may possibly provide an explanation for FBN (Klein et al. 1996a).

We found a new peaked noise feature in the NB and FB, with a centroid frequency in the range 11–54 Hz. This high-frequency peak was stronger at higher energies. It could be fitted satisfactorily with a single Lorentzian, but, in the NB, it could also be fitted with two Lorentzian components, representing a possible HBO and sub-HBO peak.

We found very low-frequency noise throughout the Z track. It exhibited abrupt changes in the power-law index and fractional rms amplitude with movement from the NB into the FB. We calculated complex cross-spectra between intensity and hardness, and discovered that VLFN is not entirely a result of movement along the Z track. We speculate that VLFN may be caused by variations in mass-accretion rate or $\eta$ that produce motion in the HID with a component both parallel, and perpendicular, to the track; or a combination of nuclear burning on the neutron star, and variations in accretion rate or $\eta$.

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APPENDIX A: CORRECTING RXTE DATA FOR DIFFERENTIAL DEADTIME AND CHANNEL CROSS-TALK

In the case of RXTE, the observed counting rate per detector $\mu$, and incident counting rate $\lambda$, can be divided into four components:1 1‘good xenon’ counting rate $\mu_{xe}$; the ‘remaining count’

1 http://rxte.gsfc.nasa.gov/docs/xte/recipes/pca_deadtime.html
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The incident and observed counting rates are related by

\[ \mu = f \lambda, \quad (A1) \]

where \( f \) is the deadtime correction factor, and is given by

\[ f = 1 - \tau_x \mu_x - \tau_i \mu_i - \tau_p \mu_p - \tau_e \mu_e \quad (A2) \]

and

\[ f = \frac{1}{1 + \tau_x \lambda_x + \tau_i \lambda_i + \tau_p \lambda_p + \tau_e \lambda_e}. \quad (A3) \]

The actual fractional rms amplitude \( r_x \) of variations in \( \lambda_x \) may be related to the observed fractional rms amplitude \( r'_x \) of variations in \( \mu_x \) by the following expression (van der Klis 1989)

\[ r_x = \frac{r'_x}{C}, \quad (A4) \]

where

\[ C = \left| 1 + \frac{\lambda_x}{\lambda_x} \frac{df}{d\lambda_x} \right|. \quad (A5) \]

To determine \( C \), we need to evaluate \( df/d\lambda_x \). Therefore, we also need to determine how \( \lambda_x, \lambda_p \) and \( \lambda_i \), depend on \( \lambda_x \). In Figs A1–A3, we present plots of \( \lambda_x, \lambda_p \) and \( \lambda_i \), respectively, versus \( \lambda_x \). The data presented are from Standard 1 mode using 16-s averages.

In Fig. A1, in the region \( \lambda_x > 3000 \text{ count s}^{-1} \text{ detector}^{-1} \), there is a roughly linear relationship between the good xenon counting rate and remaining count. In the region \( \lambda_x < 3000 \text{ count s}^{-1} \text{ detector}^{-1} \), the lower envelope of the plot also follows the linear relationship observed above 3000 count s\(^{-1}\) detector\(^{-1}\), suggesting that the relationship holds for all \( \lambda_x \). The best-fitting linear coefficient, as fitted in the \( \lambda_x \) range 3000–4600 count s\(^{-1}\) detector\(^{-1}\), was 0.085. The large scatter of points lying above the linear relationship, in the region \( \lambda_x < 3000 \text{ count s}^{-1} \text{ detector}^{-1} \), can be attributed to events from particles. This interpretation is supported by the presence of a similar scattering of points in Fig. A3.

In Fig. A2, there is a quadratic relationship between \( \lambda_q \) and \( \lambda_x \). The best-fitting quadratic and linear coefficients were \(-1.165 \pm 5 \) and 0.175, respectively. In Fig. A3, there is no clear correlation between \( \lambda_q \) and \( \lambda_x \).

From the plots presented in Figs A1–A3, we find

\[ \frac{d\lambda_p}{d\lambda_x} = 0.085. \quad (A6) \]

\[ \frac{d\lambda_q}{d\lambda_x} = -(2.33 \pm 5) \lambda_x + 0.175. \quad (A7) \]
\[
\frac{d\lambda}{d\lambda_{xe}} = 0. \tag{A8}
\]

Now we can evaluate \( df/d\lambda_{xe} \) and find \( C \)
\[
\frac{df}{d\lambda_{xe}} = -\tau_{xe} \left[ 1 + 0.085 - (2.33e-5)\lambda_{xe} + 0.175 \right] \frac{1}{(1 + \tau_{xe}\lambda_{xe} + \tau_{r}\lambda_{r} + \tau_{p}\lambda_{p} + \tau_{v}\lambda_{v})^2}. \tag{A9}
\]
\[
\frac{df}{d\lambda_{xe}} = -\tau_{xe} [1.26 - (2.33e-5)\lambda_{xe}] f^2. \tag{A10}
\]

And thus
\[
C = |1 - \tau_{xe}[1.26 - (2.33e-5)\lambda_{xe}] f| \cdot \tag{A11}
\]

We used the above expression to correct for differential deadtime and channel cross-talk in the standard manner (e.g. Lewin et al. 1992).

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