EXOSAT observations of Z sources
Kuulkers, E.

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GX 17+2: Spectral and timing behaviour of a bursting Z-source

E. Kuulkers, M. van der Klis, T. Oosterbroek, J. van Paradijs, and W. H. G. Lewin

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Abstract

We report the detection of two new bursts in EXOSAT data of the Z source GX 17+2, which we interpret to be type I bursts. No regular pulsations are observed during these two bursts nor during bursts previously detected with EXOSAT with upper limits to the pulsed amplitude of ~1.5% up to 512 Hz. Three of the four bursts occurred in the normal branch, while one occurred in the lower flaring branch.

The Z pattern in the X-ray colour-colour diagram does not move to within ~2% between the different observations. We investigated the power spectral components as function of position in the Z. The observations support the distinction of the Z sources into two sub-groups, the difference between which may be a difference in inclination.

It has been noted previously that the maximum HBO frequency in GX 17+2 is lower than the maximum HBO frequency in Cyg X–2, GX 5–1 and GX 340+0. We suggest that an asymmetry in the magnetic field giving rise to polar caps with different emission characteristics may be the origin of this. This may explain the occurrence of bursts in GX 17+2 and perhaps also the fact that they were not seen to occur in the HB.

The Poisson level in power spectra of data processed by the on-board computer of EXOSAT for several sources is found to deviate from that expected from simple variable dead time effects. We present corrections to the usually employed relations between observed intensity and Poisson level.

8.1 Introduction

Studies of the broad-band X-ray spectral and correlated timing behaviour of the brightest persistent low-mass X-ray binaries (LMXBs) have shown (see Hasinger & van der Klis 1989) that GX 17+2 belongs to the group of the so-called Z-sources. Z-sources show common characteristics: in the X-ray colour-colour diagram (CD) and hardness-intensity diagram (HID) the sources trace out a roughly “Z” shaped track. The limbs of the “Z” are called horizontal branch (HB),
normal branch (NB) and flaring branch (FB), from the top limb to the bottom limb, respectively. The sources move smoothly through the different branches, and do not jump from branch to branch. This one-dimensional motion through the “Z” is thought to be governed by the mass-accretion rate, $M$, which increases from the HB, through the NB, to the FB (e.g. Hasinger et al. 1990). The Z-sources are thought to accrete mass at a rate near the Eddington limit (e.g. Lamb 1989).

In each branch, a Z source shows a characteristic power spectrum. In the HB one sees high-frequency (15–55 Hz) quasi-periodic oscillations (QPO), called HBO, together with associated band-limited noise, called low-frequency noise (LFN), which dominates the region from $\sim 1$ Hz to the HBO frequency. In the NB one sees another type of QPO at a lower frequency (4–7 Hz), called NBO. NBO have been seen to occur simultaneously with HBO (e.g. Hasinger et al. 1990, Lewin et al. 1992). In some Z-sources (Sco X–1, see e.g. Dieters & van der Klis [1995], and GX 17+2, see e.g. Penninx et al. [1990]), the NBO merges smoothly into a higher frequency (up to $\sim 20$ Hz) QPO, called FBO when the source moves into the FB.

Two noise components have been seen to occur in all three branches. One is the very-low-frequency noise (VLFN), dominating the region below $\sim 1$ Hz. VLFN generally increases towards the FB. The other component is the high-frequency noise (HFN), which dominates the region above $\sim 20$ Hz. HFN generally decreases towards the FB (see Dieters & van der Klis 1995, van der Klis & Kuulkers 1995, and references therein).

It has become clear that on the basis of their spectral and timing behaviour the Z-sources can be roughly divided into two categories, the difference between which is a difference in inclination angle (Hasinger & van der Klis 1989, Kuulkers et al. 1994a [Chapter 3], see also Kuulkers & van der Klis 1995a [Chapter 5]). The Z-sources GX 5–1, Cyg X–2 and GX 340+0 are then viewed at a high inclination, and the Z-sources Sco X–1, GX 17+2 and GX 349+2 at a low inclination (see Kuulkers et al. 1994a, Chapter 3).

The only direct evidence of the compact stars in the Z sources being neutron stars is the observation of X-ray bursts. Of the Z-sources, up to now only GX 17+2 (Tawara et al. 1984, Kahn & Grindlay 1984, Sztajno et al. 1986) and Cyg X–2 (Kahn & Grindlay 1984, Kuulkers et al. 1994a [Chapter 6]) have been shown to display X-ray bursts. The occurrence of these irregular X-ray bursts and the lack of bursts in the other Z sources has been attributed to the high $M$ in these systems (see the review by Lewin et al. 1993).

Recently the EXOSAT data of two Z-sources have been analyzed in a detailed and homogeneous way (GX 5–1: Kuulkers et al. 1994a [Chapter 3], Sco X–1: Dieters & van der Klis 1995). The present work reports the results of a similar comprehensive study of the broad-band X-ray spectral and timing behaviour of GX 17+2. Parts of the EXOSAT data of this source have been reported elsewhere: Langmeier et al. (1986, 1990), Sztajno et al. (1986), Stella et al. (1987), Schulz et al. (1989), Hasinger & van der Klis (1989). In this study we find previously unseen bursts, place all EXOSAT bursts within the Z-diagram (a preliminary report of these bursts was given by Kuulkers et al. 1994c), and present the overall broad-band spectral and timing behaviour. The results are discussed within the framework of the magnetospheric model for Z sources and of the idea that GX 17+2 is a Z source with a relatively low inclination.

### 8.2 Observations

In this paper we analyse all available medium energy experiment (ME) argon data from EXOSAT (Turner et al. 1981, White & Peacock 1988) of GX 17+2. In Table 8.1 we present the observation log of GX 17+2. The ME had eight detectors, of which each consisted of two layers, an argon filled chamber in front of a xenon filled chamber\(^1\). Data could be obtained in different observation

\(^{1}\)In the beginning of 1985 day 232 one of the eight detectors ceased to operate.
8.3 Analysis

Table 8.1: EXOSAT Argon observation log of GX 17+2

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Day*</th>
<th>UT start (hr:min)</th>
<th>UT end (hr:min)</th>
<th>Mode*</th>
<th>Time Resolution</th>
<th>Spectral State</th>
<th>Config.</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>Aug 3/4</td>
<td>215/216</td>
<td>15:58</td>
<td>00:36</td>
<td>E4/T3</td>
<td>0.3s/8ms</td>
<td>HB/NB</td>
<td>H2</td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>Sep 5/6</td>
<td>249/250</td>
<td>21:47</td>
<td>05:21</td>
<td>E4/5/T3d</td>
<td>10/0.6s/8ms</td>
<td>HB</td>
<td>H1/H2d</td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>Sep 6/7</td>
<td>250/251</td>
<td>19:42</td>
<td>04:04</td>
<td>E5/T3</td>
<td>0.6s/6ms</td>
<td>NB</td>
<td>H1/H2</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>Aug 20/21</td>
<td>232/233</td>
<td>10:32</td>
<td>07:19</td>
<td>E5/T3</td>
<td>1s/2ms</td>
<td>NB</td>
<td>H1/H2/WA</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>Sep 15/16</td>
<td>258/259</td>
<td>16:15</td>
<td>04:48</td>
<td>E5/7/T3/4d</td>
<td>0.7s/2/4/0.25ms</td>
<td>HB</td>
<td>WA</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>Apr 3/4</td>
<td>093/094</td>
<td>04:09</td>
<td>11:10</td>
<td>E2/5/7/T4/5n</td>
<td>1.4/1s/8/0.25/1ms</td>
<td>NB/FB</td>
<td>WA</td>
<td></td>
</tr>
</tbody>
</table>

4Jan 1 = day 1.
5T = HER mode = High Energy Resolution mode, HTR = High Time Resolution mode.
6Array configuration on source: HI = "Half 1", H2 = "Half 2", WA = whole array.
7From 21:47 - 22:07 HER4 (H1), rest HER5/HTR3 (H2).
8Rest HER5/HTR3 (H2).
9From 19:41 - 19:51 H1, rest H2.
11From 16:15 - 03:13 HER7/HTR3 (HER7 effectively one energy band: 1.4-4.1 keV; HTR3 from 16:15 - 22:58 xenon, rest argon), rest HER5/HTR4.
12HER2: day 099 15:28-20:31 (1s) and day 099 22:55-day 094 09:07 (4s); HER5: day 094 09:11-11:10; HER7: day 093 04:09-15.14 and day 093 20:36-day 094 09:07; HTR4: day 093 15:25-20:31; HTR5: day 093 04:09-15:14 and day 093 20:39-day 094 11:10.

It was possible to obtain data with a medium spectral resolution (HER2, HER3, HER4, HER5; the different HER-modes denote the different options to transmit data from individual or data combined from several or all detectors), or with a high time resolution (HTR3, HTR4, HTR5). Alternatively one could obtain data in two (e.g. 1985 day 258/259) or four energy bands (e.g. 1986 day 093/094) at a high time resolution (HER7). The HER-modes could be run simultaneously with one of the HTR-modes. Either one half of the array of eight detectors ("half 1" [HI] or "half 2" [H2]) was pointed to the source while the other half monitored the background, or the whole array (WA) was pointed to the source (see Table 8.1).

The HER-modes are processed by the EXOSAT onboard computer (OBC), which produces large dead-time effects. In our analysis of CDs and HIDs (see below) we determine the dead-time factor from the qualified event rates (collected each 32s for each detector), which are (almost) unaffected by dead time. Of the HTR-modes, only the HTR4 mode is processed by the OBC. The HTR4 mode provides the count rate in only one (chosen) energy band at the highest time resolution available with EXOSAT (~0.25 ms). The HTR4-mode observations at 1985 day 258/259 and at 1986 day 093/094 provided the count rate in the 1.4-11.4 keV band and in the 1.2-19.9 keV band, respectively.

At 1986 February 13th (day 044) problems started with the EXOSAT attitude and orbit control system (AOCS), see White (1986). Between March 27th (day 086) and April 9th (day 099) stable pointing was regained within 5 arcmin. This resulted in uncertainties in the detected intensity, due to a varying collimator response. In principle one could use the star tracker attitude control data (collected every 8 or 16 s) to correct for this. However, due to problems during the 1986 day 093/094 observations with the star tracker and gyros this was not possible for this observation period. We therefore used these data only to produce a CD and not for the HIDs. After April 9th (day 099) stable pointing was lost again, which resulted in a complete loss of the satellite. On May 9th (day 129) EXOSAT re-entered the Earth's atmosphere (White 1986).

8.3 Analysis

For the spectral analysis we use CDs and HIDs. These diagrams are created using either three or four energy bands (e.g. Hasinger & van der Klis 1989). Since the observations during 1986...
day 093/094 provided only four energy channels, we decided to analyse all the data using the
energy bands corresponding to these channels. We found that three energy bands (i.e. combining
two channels) gave the best separation of the branches of GX 17+2 in the CD: 1.2–4.7 keV, 4.7–
6.6 keV and 6.6–19.9 keV. In the CD and HID s the soft colour is defined as the ratio of the count
rate in the second energy band to the count rate in the first energy band, while the hard colour
is defined as the ratio of the count rate in the third energy band to the second energy band. The
"intensity" used in the HID s is the count rate in the 1.2–19.9 keV band, corrected for dead time
and collimator response (as determined by Kuulkers et al. 1994a, see Chapter 1). All points in
the CD and HID s are 200 s averages.

In order to investigate the fast timing behaviour of GX 17+2 we performed fast Fourier
transforms (FFTs) on successive 8 s or 16 s (depending on source state: when the source was
in the HB we made 8 s FFTs). This was done to avoid the contribution of the VLFN when
fitting LFN in these power spectra, Section 8.4.4.2) and 512 s blocks of data of all the high-time
resolution argon data. When analysing power spectra of Z sources, one recognizes several power
spectral components (Hasinger & van der Klis 1989, see also Kuulkers et al. 1994a [Chapter 3],
Dieters & van der Klis 1995): a constant level due to counting noise (so-called Poisson level)
modified by dead-time processes, three "noise" components, VLFN (represented by a power
law), LFN and HFN (both represented by a power law with exponential cut-off), and two kinds
of QPO, HBO and NBO/FBO (both represented by Lorentzians). In some cases the HBO show
a second harmonic, which is also represented by a Lorentzian. For completeness we give the
functional shapes of these components (see also Hasinger & van der Klis 1989, Kuulkers et al.
1994a [Chapter 3]):

- The VLFN is given as: \( P_{\text{VLFN}}(\nu) = A_{V} \nu^{-\alpha_{V}} \), where \( \nu \) is the frequency, \( \alpha_{V} \) the power-law
index, and \( A_{V} \) the normalization constant.

- The LFN and HFN are given as: \( P_{\text{LFN,HFN}}(\nu) = A_{L,H} \nu^{-\alpha_{L,H}} e^{-\nu/\nu_{L,H}} \), where \( \alpha_{L,H} \) is the
power-law index, \( \nu_{L,H} \) the cut-off frequency, and \( A_{L,H} \) the normalization constant, for the
LFN \( (L) \) and HFN \( (H) \) respectively. In the Z sources \( \alpha_{L} \) was found to be consistent with
zero (Hasinger & van der Klis 1989), at which value we fixed this parameter.

- The HBO, its harmonic, the NBO and the FBO are broad peaks with a centroid frequency \( \nu_{c} \). These peaks are described by Lorentzians: \( P_{\text{QPO}}(\nu) = A_{Q} \left( \nu - \nu_{c} \right)^{-1} \left( \Delta \nu / 2 \right)^{2} \), where \( \Delta \nu \) is
the full width at half maximum (FWHM) of the QPO and \( A_{Q} \) a normalization constant.

The strength, expressed in terms of the fractional rms, of the various noise components is
determined by integrating their contribution over a certain frequency range (VLFN: 0.001–1 Hz
[512 s FFTs] and 0.01–1 Hz [8/16 s FFTs]; LFN and HFN: 0.01–100 Hz). Since the HER7 and
HTR4 data suffer from large (variable) dead-time effects (see below), we corrected the rms
strengths of the power spectral components for these effects (see van der Klis 1989, Kuulkers et
al. 1994a [Chapter 3]).

The Poisson levels of the power spectra of the HTR3/HTR5 modes were determined using
the relation between Poisson level and observed raw count rate (Van der Klis 1989b, Berger &
van der Klis 1994, see also Appendix A). In power spectra of data from the HER7 and HTR4
modes, the OBC dead time affects the Poisson level to a large extent (see e.g. Kuulkers et al.
1994a, Chapter 3). We refer to Appendix A for a more detailed discussion of this effect.
The power spectrum of the Poisson noise in the power spectral data from OBC processed data
at frequencies higher than \(~120 \text{ Hz}\) is no longer constant, but increases to higher frequencies
(Tennant 1987). Most HER7 mode data provided a Nyquist frequency of 128 Hz or lower, so
this only had a significant effect in the HTR4 mode, which provided a Nyquist frequency of
2048 Hz. We used the Poisson level as a free parameter in the fits to the HER7 power spectral
8.4 Results

8.4.1 New bursts

In Figs. 8.1a–e we show the light curves of all observation periods except 1986 day 093/094 at a 5 s time resolution. In Figs. 8.1c and d we see that the smooth overall variations are interrupted by two bursts, which were already reported by Sztajno et al. (1986).

As noted in the previous section, the pointing during the observation period 1986 day 093/094 was only stable to within 5 arcmin. In Fig. 8.2 we display the data (Fig. 8.2a, 5 s time resolution) together with a soft-colour curve (Fig. 8.2b, 200 s time resolution) to show the overall branch behaviour. Although variations due to the varying collimator response are visible, one can also see that the variations in the FB are more irregular than in the NB.

If one takes a closer look to the 1986 day 093/094 data two sharp peaks in the light curve seem to disturb the relatively smooth variations (~36,000 and ~104,000 s after the start of the observations). We investigated these peaks and found that they were X-ray bursts, which had been previously overlooked. The housekeeping data ruled out a solar particle origin (see also e.g. Kuulkers et al. 1994a, Chapter 6). In Figs. 8.3a and b we display these bursts at a higher
Figure 8.2. EXOSAT ME light curve (a) and soft colour curve (b) of the observation period 1986 day 093/094. Intensity is the dead-time and background corrected count rate in the 1.2–19.9 keV range, while the soft colour is the ratio of the count rate in the 4.7–6.6 keV and the count rate in the 1.2–4.7 keV band. The intensities are not corrected for collimator response (see text). Two new bursts can be seen at (~36 000 and ~104 000 s after the start of the observation). The start time of the observation period can be found in Table 8.1.

Figure 8.3. High time resolution (0.5 s) argon light curves of the bursts which occurred during 1986 day 093 (a) and 1986 day 094 (b), together with their colour (ratio of the count rates in the 4.7–19.9 keV and 1.2–4.7 keV bands) curves, in c and d, respectively. During the 1986 day 094 burst the observations were interrupted for mode changes. The qualified event rate from the housekeeping data is therefore also plotted in b (with symbol ○) to show the overall burst profile.
8.4 Results

Table 8.2: Upper limits to modulation strength

<table>
<thead>
<tr>
<th>Burst</th>
<th>$\nu_{NY}^a$ (Hz)</th>
<th>Upper limit (%)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>64</td>
<td>6.1</td>
</tr>
<tr>
<td>II</td>
<td>256</td>
<td>1.0</td>
</tr>
<tr>
<td>III</td>
<td>512</td>
<td>2.1</td>
</tr>
<tr>
<td>IV</td>
<td>512</td>
<td>1.9</td>
</tr>
<tr>
<td>II+III+IV</td>
<td>256</td>
<td>0.9</td>
</tr>
<tr>
<td>III+IV</td>
<td>512</td>
<td>1.5</td>
</tr>
</tbody>
</table>

$^a$ $\nu_{NY}$ is the Nyquist frequency.

$^b$ 99% confidence upper limit
to the fractional sinusoidal amplitude
of the total flux.

time resolution (0.5 s). The intensity in these plots is the total HTR5 count rate, corrected for
dead time and background. The second burst straddled two EXOSAT observation segments
and is therefore interrupted. Observation modes were switched at that time, and no data were
available for $\sim$200 s. Only the scientific monitoring was enabled during this time interval, which
provided qualified event rate data. Therefore, in Fig. 8.33, we overlayed the HTR5 light curve
of the burst with a light curve of the qualified event rate data (collected every 32 s) light curve.

The bursts are not related to the changes in the pointing of the satellite. The events rise
within 1 s, which is much faster than the pointing variations (typically $\sim$100 s). In Figs. 8.3c and
d we display colour (where colour is defined as the ratio of the count rates in the 4.7–19.9 keV
energy band and the count rates in the 1.2–4.7 keV energy band) curves for the two events. In
the case of pointing variations one does not expect to see such colour changes, so they must be
intrinsic to the source. The colour changes during the bursts indicate spectral softening.

8.4.2 Burst properties

The first of the two new bursts started at 1986 day 093 UT 14:04:57 and lasted for $\sim$100 s, while
the second started at 1986 day 094 UT 9:05:40 and lasted $\sim$300 s. Whenever possible, we checked
whether other bursts occurred during time intervals when the OBC was not operational using
the qualified event data. None were found, from which we infer that the two bursts observed
occurred $\sim$19 hr after each other. Since we could not determine the exact pointing positions
during the 1986 observations (and therefore the collimator response), which changed on time
scales of $\sim$100 s, it was not possible to determine the X-ray burst properties $\alpha$ (ratio of the
average persistent flux to the time-averaged flux emitted in the bursts) and $\gamma$ (ratio of the mean
persistent pre-burst flux and the net peak burst flux) (see Lewin et al. 1993). However, since
the recurrence time between the first and the second burst was long and the peak net burst flux
is smaller than the persistent flux, we expect $\alpha$ to be very large (larger than 1000) and $\gamma > 1$.
Spectral data (HER2) were only available during the second burst, but because the burst was
interrupted $\sim$75 s after it started, and due to the uncertain varying collimator response, we did
not perform a detailed spectral analysis of these data.

To investigate in which branch the source was when the 1986 bursts and the bursts detected
by Sztajno et al. (1986) occurred, we created a CD of all the data (except the 1983 data, see
Section 8.4.4.1). This CD is shown in Fig. 8.4a; the different branches are indicated. We found
Figure 8.4. (a) EXOSAT X-ray colour-colour diagram and (b, c) hardness-intensity diagrams of GX 17+2. Soft colour is defined as the ratio of the count rates in the 1.2–4.7 keV and the 4.7–6.6 keV bands, hard colour as the ratio of the counts in the 6.6–19.9 keV and the 4.7–6.6 keV bands. The intensity (corrected for background, dead-time and collimator response) is defined as the count rate in the 1.2–19.9 keV band. Different symbols refer to different observation periods, which are given in the lower right part of (a). Each point represents a 200 s average. Typical error bars are given in each frame. HB (horizontal branch), NB (normal branch) and FB (flaring branch) are indicated. In a we give the position in the CD at the time the different bursts (1984 day 250/251: I, 1985 day 232: II, 1986 day 093: III, 1986 day 094: IV) occurred.

that the small 1984 burst (I) occurred when GX 17+2 was in the upper NB, while the other bursts (1985 day 232: II; 1986 day 093: III; 1986 day 094: IV) occurred in the middle NB or near the NB/FB apex. None of the bursts occurred in the HB. No clear dependence between duration of the bursts and position in the Z could be found.
8.4 Results

8.4.3 Pulsations during the bursts?

It was recently suggested that bursts in luminous sources, such as GX 17+2, might have their origin in small areas or patches on the neutron star surface (Bildsten 1993, 1995). Due to the neutron star spin (which is expected to be much faster than the burst duration) one then expects to see a pulsating signal (see also Schoelkopf & Kelley 1991). We performed FFTs of the count rate during the bursts to search for sharp peaks in the power spectra, which might reveal the spin period. We followed the same procedure as Vaughan et al. (1994b) for searching pulse periods in persistent signals. When no signal is found above the detection threshold an upper limit is set to any pulse signal within a chosen frequency range. This upper limit on the power is then translated into a maximum modulation strength for an assumed purely sinusoidal pulse signal.

We performed 8s, 256s and 64s FFTs, for the 1984, 1985 and 1986 bursts, respectively. We also combined the two 1986 bursts and these bursts together with the 1985 burst. When combining bursts, we did not take into account the 1984 burst, since the time resolution was relatively low. We performed 64s FFTs for the combined bursts. We found no evidence for any periodic signal above the 99% confidence detection level due to a rotating patch upon the neutron star. The 99% confidence upper limits to the sinusoidal amplitude for a periodic modulation are given in Table 8.2. We find no source signal in the power spectra during the bursts with an upper limit of ~1% sinusoidal fractional amplitude for the 0–256 Hz frequency range, and ~1.5% for the 256–512 Hz frequency range.

8.4.4 Spectral and timing behaviour

8.4.4.1 Broad-band spectral analysis

The CD of all HER observations, except the data obtained in 1983, was already shown in Fig. 8.4a. In Figs. 8.4b and c we display both HIDs of data obtained of GX 17+2 after 1983. As already noted in Section 8.2, the 1986 data are missing in the HIDs, because of pointing problems. The CD and HIDs of the 1983 day 215/216 data can be found in Figs. 8.5a–c. The data points in these figures have been connected to show more clearly the presence of the FB. Comparing the CDs of the 1983 data and other observations, it appears that the 1983 data are
placed at higher soft and hard colours with respect to the other observations. This is also clear when one compares the HIDs of the 1983 data (Figs. 8.5b and c) with the other observations (Figs. 8.4b and c). Note that the overall intensities in both HIDs are comparable. In the CD, all data obtained after 1983 fall within the same Z-track, i.e. no differences in the position of the branches in the CD for these observations were found. We therefore suspect the shift of the 1983 data to be an effect of the instrument, although formally we cannot rule out the possibility that it is real, i.e. intrinsic to the source. However, CDs of other sources show similar shifts in the position of the tracks of the 1983 data with respect to the tracks of data obtained after 1983: GX5-1, CygX-2, GX349+2, 4U 1636–53 and SerX-1 (see Kuulkers et al. 1995c [Chapter 4], and references therein). The CDs of GX17+2 and these sources were all made in the same way. Since all sources show the same effect, this shift is unlikely to be related to the sources themselves, but must be instrumental. We may therefore conclude that the Z-diagram of GX17+2 is fairly stable in the CD (within ~2% ) and does not show evidence for secular motion.

The HID s of GX17+2 seem to be also quite stable, however, one data set (the 1985 day 258 data) is placed at higher intensities with respect to the other data (by ~8%). Since instrumental changes between the 1984 day 249/250 and the 1985 day 258/259 data may contribute up to 3% in intensity (see Kuulkers & van der Klis 1995b, Chapter 7) we think this shift in intensity in the HID is probably intrinsic to the source. More observations are needed to verify if this effect is real.

As can be seen in Figs. 8.4a–c and 8.5a–c, GX17+2 was observed in all three spectral branches (see also Table 8.1). The HB is clearly not horizontal in the CD, but nearly vertical, as was already noted by others (e.g. Hasinger & van der Klis 1989); in the other diagrams it has different orientations. Due to the unfortunate choice of HER7 energy boundaries when the 1986 observations were performed, the FB is positioned close to the NB (Fig. 8.4a). This has the effect that the FB is oriented above the NB in Fig. 8.5b, while it falls along the NB in Fig. 8.5c.

\[ \text{This does not, however, affect the conclusion derived by Kuulkers et al. (1994a, Chapter 3) that the "Z" pattern of GX 5–1 shows intrinsic shifts from one observation to the next.} \]
Figure 8.6. Three examples of average power spectra corresponding to different segments in $S_Z$. The corresponding fits are shown for clarity, and the power spectral components are indicated. (a) Power spectra for data of 1985 day 258/259 when GX 17+2 was in the upper HB near $S_Z\sim0.1$. Both the HBO and its harmonic can be seen, as well as the peaked noise component LFN. (b) Power spectra for data of 1985 day 232/233 during the NB near $S_Z\sim1.8$. The NBO can be seen near 7.6 Hz. (c) Power spectra for data in the lower FB during 1986 day 093/094 near $S_Z\sim2.4$. The FBO can be seen near 16 Hz.

8.4.4.2 Power spectral analysis

8.4.4.2.1 Introduction

To study the short term (1 ms–500 s) behaviour of GX 17+2, we investigated the power spectra as obtained by the FFT algorithm from the high timing resolution data (see Section 8.3). We studied the power spectral components as a function of position along the $Z$. We used a one-dimensional parameter, $S_Z$, which measures the distance along the $Z$, as was first introduced by Hertz et al. (1992). The scale in the CD was fixed by assigning $S_Z$ values of 1 and 2 for the HB/NB apex and the NB/FB apex, respectively (see Dieters & van der Klis 1995, Kuulkers et al. 1994a [Chapter 3]), in the CD of Fig. 8.4a. The same scaling was also used for the 1983 day 215/216 observations. During the first part of the 1985 day 258/259 observation (16:15–03:13) we could not determine $S_Z$ from the CD, since data were only available in effectively one broad low energy band. However, since the position in the HB is dependent on intensity we could determine $S_Z$ in an indirect way. For the second part of the 1985 day 258/259 observation we had sufficient data to determine the dependence of intensity on $S_Z$ in the relevant channel. We used this relation to determine $S_Z$ values in the first part of the observations. $S_Z$ ranges from $\sim0$ in the upper HB, to $\sim4.5$ in the upper FB. In Figs. 8.6a–c we show average power spectra from the different branches (HB, NB and FB). The various spectral components are indicated.

In Tables 8.3 and 8.4a and b we give the results of the power spectral fits as a function of $S_Z$ for the 512 s FFTs, 8 and 16 s FFTs, respectively. In Table 8.5 we give the results for the harmonic when present in the power spectra as a function of $S_Z$. In Figs. 8.7a–i several power spectral parameters for the different observation periods as a function of $S_Z$ are shown in a graphical way. In the next sections we will discuss the results for each power spectral component. The 1985 day 258/259 HER7 and HTR4 data are not used in our discussion since they have different energy bands with respect to the other data (see Table 8.1); only for the
### Table 8.3: Results of power spectral fits of 512s FFTs

<table>
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<tr>
<th>Obs. period</th>
<th>VLFN</th>
<th>LFN</th>
<th>HFN</th>
<th>QPOb</th>
<th>( \chi^2_{\text{red}} )</th>
<th>dof</th>
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<td>9.85 ± 0.18</td>
<td>58 ± 0.84</td>
<td>74 ± 1.5</td>
<td>2.3 ± 0.9</td>
<td>12 ± 1.7</td>
</tr>
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<td>9.85 ± 0.18</td>
<td>74 ± 1.5</td>
<td>2.3 ± 0.9</td>
<td>12 ± 1.7</td>
<td>0.8 ± 0.9</td>
</tr>
<tr>
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<td>1.351 ± 0.057</td>
<td>9.85 ± 0.18</td>
<td>74 ± 1.5</td>
<td>2.3 ± 0.9</td>
<td>12 ± 1.7</td>
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<td>12 ± 1.7</td>
<td>0.8 ± 0.9</td>
</tr>
<tr>
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<td>day 358</td>
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### Notes

- **VLFN**: Whenever a component was not present in the average power spectrum it is indicated by "-".
- **LFN** and **HFN**: The *H*0 or *N*0.0.
- *All errors are determined from an error scan through the \( \chi^2 \) space using \( \Delta \chi^2 = 1.0 \).*
- *The Poisson level was a free parameter in the fits to these data.*
- *Effective energy range: 1.4-4.1 keV.*
- *Effective energy range: 1.2-10.8 keV.*
- *Parameter fixed.*
- *Affected by collimator response variations, see text.*
### Table 8.4a: Results of power spectral fits of 8s FFTs

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<th>err</th>
<th>rms</th>
<th>err %</th>
<th>LFN</th>
<th>err</th>
<th>$v_L$ (Hz)</th>
<th>err</th>
<th>rms</th>
<th>err %</th>
<th>HFN</th>
<th>err</th>
<th>$v_H$ (Hz)</th>
<th>err</th>
<th>rms</th>
<th>err %</th>
<th>QPO</th>
<th>err</th>
<th>$\Delta v$ (Hz)</th>
<th>err</th>
<th>$\nu$ (Hz)</th>
<th>$\chi^2_{\text{red}}$</th>
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<td>175</td>
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<td>aWhenever a component was not present in the average power spectrum it is indicated by &quot;-&quot;.</td>
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<tr>
<td>bHB or NBO.</td>
</tr>
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<td>cAll errors are determined from an error scan through the $\chi^2$ space using $\Delta\chi^2 = 1$.</td>
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<td>dThe Poisson level was a free parameter in the fits to these data.</td>
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<td>eEffective energy range: 1.4-1.5 keV.</td>
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<tr>
<td>fEffective energy range: 1.4-4.1 keV.</td>
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<tr>
<td>gNegative $S_2$ due to scaling; this indicates that the HB is somewhat longer than the NB.</td>
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Table 8.4b: Results of power spectral fits of 16 s FFTs\(^a\)

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<th>obs</th>
<th>err</th>
<th>rms</th>
<th>obs</th>
<th>HFN</th>
<th>err</th>
<th>rms</th>
<th>obs</th>
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<td>0.7</td>
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</tbody>
</table>

\(^a\)Whenever a component was not present in the average power spectrum it is indicated by "-".

\(^b\)NBO.

\(^c\)All errors are determined from an error scan through the \(\chi^2\) space using \(\Delta \chi^2 = 1\).

\(^d\)The Poisson level was a free parameter in the fits to these data. Effective energy range: 1.3-19.8 keV.
8.4 Results

Table 8.5: Harmonic parameters during 1985 day 258/259

<table>
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<tr>
<th>$S_z$</th>
<th>err</th>
<th>rms (%)</th>
<th>$\Delta \nu$ (Hz)</th>
<th>err</th>
<th>$\nu$ (Hz)</th>
<th>err</th>
<th>rms_H / rms_Q</th>
<th>err</th>
<th>$\Delta \nu_H / \Delta \nu_Q$</th>
<th>err</th>
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<tbody>
<tr>
<td>8 s FFTs</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>0.079</td>
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<td>2.5</td>
<td>±0.6</td>
<td>+11</td>
<td>52</td>
<td>±2</td>
<td>0.7</td>
<td>0.2</td>
<td>1.5</td>
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<td>+9</td>
<td>49</td>
<td>±2</td>
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<td>0.2</td>
<td>2.9</td>
<td>1.3</td>
</tr>
<tr>
<td>512 s FFTs</td>
<td></td>
<td></td>
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<tr>
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<td>±3</td>
<td>49.2</td>
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<td>±4</td>
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<td>±0.6</td>
<td>0.8</td>
<td>0.3</td>
<td>1.4</td>
<td>0.9</td>
</tr>
</tbody>
</table>

*a All errors in the power spectral parameters are determined from an error scan through the $\chi^2$ space using $\Delta \chi^2 = 1$.
*b Ratio of the harmonic rms (rms_H) and the HBO rms (rms_Q).
*c Ratio of the harmonic FWHM ($\Delta \nu_H$) and the HBO FWHM ($\Delta \nu_Q$).

discussion of the HBO FWHM and frequency we include the HTR4 data, since these parameters are independent of the energy (Penninx et al. 1990, Penninx et al. 1991, Lewin et al. 1992).

8.4.4.2.2 Very-low-frequency noise (VLFN)

The VLFN was one of the components which was detected in all spectral branches, consistent with previous observations. The VLFN rms and its power law index are plotted vs. $S_z$ in Figs. 8.7a and b, and Figs. 8.7c and d, for the 512 s FFTs and 16 s FFTs, respectively. In Figs. 8.7a and b we did not include the 1986 day 093/094 data. As can be seen in Table 8.3 the VLFN rms during these observations are constant between 5 and 6%, while the rms in the other observations in the lower NB indicate values of around 1%. We attribute this effect to the intensity variations due to the changing collimator response on time scales of larger than ~100 s, which also causes a leakage of power from still lower frequencies into the passbands of the power density estimators with nominal frequencies in the VLFN frequency range (see Deeter 1984). The power law index during the 1986 093/094 observations, about 2, is consistent with low frequency leakage. We estimate that the changing collimator response contributes up to ~5% to the VLFN source rms.

The changing collimator response only affects frequencies below 0.01 Hz. This is clear from Figs. 8.7c and d, where we included the 1986 day 093/094 data. The VLFN components, here measured only down to 0.01 Hz, fall along the other data points in both figures, and do not show an instrumental difference.

The VLFN rms is lowest (~0.5%) in the upper HB and the upper NB. It shows a local maximum in the middle HB of ~1%. From the lower NB to the upper NB the rms increases to ~1.5%. From the 16 s FFTs we infer that the VLFN strength continues to rise from the lower FB to the upper FB, up to at least 3%.

From the upper HB to the middle NB the VLFN power law index seems to be anti-correlated with its rms between ~0.8 and ~2. In the lower NB the power law index has values of around
1.5 From the 16 s FFTs we infer that in the upper FB the power law index is about 2 (note that this is similar to the 512 s FFTs), as expected from leakage effects from slow (source) intensity variations (see above). No clear correlation with other power spectral parameters is seen.
8.4 Results

8.4.4.2.3 Low-frequency noise (LFN)

The LFN is peaked (see e.g. Fig. 8.6b) as is clear from the negative LFN power law index values between -1.5 and 0 (see Section 8.3), with cut-off frequencies between 1 and 3 Hz. The rms of the LFN increases from about 1.5% in the upper NB to about 3% in the upper HB (Tables 8.3 and 8.4a).

The large uncertainty in the LFN cut-off frequency in the upper NB and the low rms indicates that the LFN vanishes in this part of the NB. Indeed, in the rest of the NB and in the FB no evidence for LFN was found.

8.4.4.2.4 High-frequency noise (HFN)

The HFN is the second component which is present in all branches, see Figs. 8.7e and f for the 512s FFTs, and Table 8.4a and b for the 8 and 16 s FFTs, respectively. It is, like the VLFN, not correlated with any of the other power spectral components. The rms strength of the HFN shows a clear trend from the upper HB to the middle NB. It decreases from about 5.3% to about 2.5%. From the middle NB to the FB no trend is seen in the rms, and has values preferentially between 2 and 3%.

The cut-off frequency is badly determined in many of the power spectra, mainly due to the relatively low Nyquist frequencies (64 Hz) in the 1984 day 249/250 and 250/251 data. Whenever the HFN cut-off frequency could be reasonably determined we found preferred values between 10 and 50 Hz.

8.4.4.2.5 QPO: HBO, NBO and FBO

HBO were only found in the 1985 day 258 data in the upper HB (Tables 8.3 and 8.4a and b). There are indications of a very weak HBO component around the expected frequency range in the 1984 day 249/250 data, but its significance is small. Moreover, the time resolution of the timing data during this observation is low, and therefore also the Nyquist frequency (see previous paragraph). The QPO frequency increases from the upper HB to the middle HB from
\( \sim 23 \) to \( \sim 28 \) Hz. Its FWHM and rms are consistent with a decrease with increasing \( S_Z \) of \( \sim 7 \) to \( \sim 2 \) Hz and \( \sim 2.5\% \) to \( \sim 1\% \) respectively. It disappears below \( \sim 1\% \) in the lower HB.

The HBO harmonic is only seen at the lowest \( S_Z \) values (see Table 8.5) and consistent with having a frequency twice the HBO frequency (Table 8.3 and 8.4a). The harmonic has a FWHM between 10 and 20 Hz and rms of about 2.5\%, i.e. as strong as the HBO itself (see also Table 8.5).

NBO with frequencies between 5 and 7 Hz were only detected in the middle and lower NB, with an rms between 1.5 and 2.5\%, and FWHM between 2 and 6 Hz (Figs. 8.7g–i).

In the 1986 day 093/094 data we found evidence for FB QPO (FBO) in the lower FB (Figs. 8.6c), with a centroid frequency of \( \sim 16 \) Hz, FWHM of \( \sim 7 \) Hz and rms of \( \sim 2\% \).
8.5 Discussion

8.5.1 Two groups of Z sources

GX17+2 and the other Z sources GX340+0, GX349+2, GX5–1, Sco X–1 and Cyg X–2 form one group with similar behaviour, i.e. three branches with correlated fast timing behaviour (Hasinger & van der Klis 1989). It has been shown, however, that GX17+2 shares properties with Sco X–1 and GX349+2, which are distinct from GX5–1, Cyg X–2 and GX340+0 (Hasinger & van der Klis 1989, Penninx et al. 1991, Kuulkers et al. 1994a [Chapter 3]). The latter sources, for example, show secular variations in the position of the Z pattern in the CD by typically ~7% (which are recurrent in the case of Cyg X–2, see Kuulkers et al. 1995c [Chapter 4]) and dipping behaviour in the FB, while the former sources show a fairly stable Z pattern and flares in intensity in the FB. We showed that in the CD the position of the Z-track of GX17+2 is indeed stable to within 2%.

The origin of these two groups may be a difference in inclination angle (see Kuulkers et al. 1994a [Chapter 3], and references therein). This is based on optical observations of the sources Cyg X–2 (Cowley et al. 1979) and Sco X–1 (Crampton et al. 1976) which indicated inclinations of 65–75° and 15–40°, respectively, and the fact that intensity decreases in the FB of the group GX5–1, Cyg X–2 and GX340+0 (this is interpreted as obscuration of the central emission by the inner disk when it puffs up near the Eddington limit). Inclination plays a key role in explanations for (i) the secular variations in the Z pattern (e.g. Kuulkers et al. 1994a [Chapter 3], 1995c [Chapter 4]), (ii) the shortness of the FB in GX5–1 and (iii) the FB QPO found in Cyg X–2 (Kuulkers & van der Klis 1995a, Chapter 5). Secular variations (i) are expected if our view of the inner regions changes due to a changing geometry of structures in the orbital plane (see Kuulkers et al. 1994a [Chapter 3], 1995c [Chapter 4]). At high inclination, one expects that in the FB the puffed up inner disk hides our view of the inner regions already for lower accretion rates (GX5–1) than at relatively lower inclination (Cyg X–2 and GX340+0), which results in a short FB (ii) in GX5–1 (see Kuulkers & van der Klis 1995a [Chapter 5]). At special viewing angles, in the FB the upper edge of the puffed up inner disk may just intersect our line of sight to the inner regions. If this edge moves up and down (quasi) periodically (due to disk oscillation) one expects to see QPO (iii) when the viewing angle is just right, as is observed in Cyg X–2 (Kuulkers & van der Klis 1995a [Chapter 5]). Recently inclination effects have been proposed to explain X-ray properties seen in black hole (candidate) systems (van der Klis 1995c), which show power spectral behaviour that is in some respects similar to Z sources and atoll sources (e.g. van der Klis 1994a,b, 1995a,b).

Several other properties in Z sources also appear to correlate with the division into two groups, but have still to be explained in the framework outlined above:

- The observation of peaked LFN in GX17+2 and Sco X–1 (see e.g. Hasinger & van der Klis 1989) and maybe occasionally peaked HFN in GX17+2 (Penninx et al. 1990), while the by hypothesis high inclination sources show non-peaked LFN. We note that atoll sources also show bimodal behaviour in their HFN, i.e. peaked and non-peaked noise. It has been suggested that atoll HFN is similar to Z source LFN (van der Klis 1994b). The different HFN shapes in atoll sources could therefore also be a manifestation of high versus low inclination in these sources.

- A vertical (short) HB in the Sco X–1 group versus a horizontal HB (with an upward bend at the lowest M) in the Cyg X–2 group.

The following property also appears different in the two groups, but is hard to fit in the inclination framework: GX17+2 and Sco X–1 are only occasionally found in the HB, and GX349+2
never, while GX 5−1, Cyg X−2 and GX 340+0 are frequently found in the HB, but only occasionally in the FB. Moreover, the time the sources in the Sco X−1 group spend in the FB is much larger (>12 hr) than the sources in the Cyg X−2 group (<2 hr). In other words, the sections of the Z which are covered by the two groups, are slightly shifted along the Z with respect to each other, with the low inclination sources covering a section corresponding to a somewhat higher M range. It is hard to understand how this could have its origin in the inclination at which we view the different groups of Z sources, unless viewing geometry affects the M level at which branch branch transitions occur in the CD and HIDs. Careful study of fast timing properties as a function of S2 can in principle show whether this is the case, but the available data is not sufficient to make a strong case either way.

8.5.2 Bursts in GX 17+2

We have detected two new bursts in GX 17+2 during the observations in 1986. One burst was about 100 s long, while the other (which occurred ~19 hr after the first one) was ~300 s long. Previously Sztajno et al. (1986) had found two other bursts in the 1984 and 1985 data of EXOSAT, which lasted ~10 and ~300 s. Bursts were also observed with other X-ray instruments: one with Einstein (~10 s, Kahn & Grindlay 1984) and four with Hakucho (two with e-folding times of ~100 s and two with e-folding times of ~300 s). The duration of the bursts might have a trimodal distribution (two are ~10, three are ~100, and four are ~300 s long), but obviously more observations are needed to verify this. All bursts have large α values (>1000) and γ > 1 (net peak burst flux is smaller than the average persistent flux). To our surprise, we found that the EXOSAT bursts occurred in the NB and lower FB, i.e. near Eddington mass accretion rates; none were found in the HB, when M is lowest.

From the fact that the two new bursts show spectral softening during their evolution, we conclude that, like the bursts reported by Sztajno et al. (1986) in this source, they are type I X-ray bursts; i.e. they are caused by thermo-nuclear flashes on the surface of the neutron star (Hoffman et al. 1978, see also Lewin et al. 1993 and references therein).

It was recently suggested that rotating burning patches on the neutron star surface during X-ray bursts may produce regular pulsations (Bildsten 1993, 1995, see also Schoelkopf & Kelley 1991). We searched for such pulsations in all four EXOSAT bursts, but none were found, with upper limits for the modulation strength of ~1% (if signal is sinusoidal). So, no evidence for the spin of the neutron star is found during the bursts, a conclusion also derived for for a large sample of regular bursts from other sources observed with EXOSAT (Jongert et al. 1998b), and for the persistent emission of GX 17+2 (Vaughan et al. 1994b).

Only one other Z source has also been observed to display X-ray bursts, i.e. Cyg X−2 (Kahn & Grindlay 1984, Kuulkers et al. 1995a [Chapter 6]). These bursts, although much smaller than those in GX 17+2, are also thought to be due to thermo-nuclear flashes on the neutron star, since several burst properties resemble those of bona fide type I bursts (see Kuulkers et al. 1995a [Chapter 6]). So, both Cyg X−2 and GX 17+2 show type I bursts, which indicates that the compact star in Z sources is a neutron star. High luminosity LMXBs tend to show irregular bursting behaviour (Lewin et al. 1993), i.e they show bursts after long and variable waiting times. This is most probably due to the high mass accretion rate, M (see Lewin et al. 1993). Extrapolating this trend to even higher M systems, i.e. the Z sources which are thought to accrete matter at near-Eddington rates (see Lamb 1989), one does not expect to see bursts at all in these sources. This problem may be circumvented if M is lower in GX 17+2 as compared to the other Z sources. However, in the NB M is thought to be approximately the same in the NB of all Z sources (Hasinger & van der Klis 1989), i.e. near-Eddington (Lamb 1989), so bursts would then be expected in the other Z sources as well. From the presence of HBO in Z sources one derives that they contain a neutron star with a non-negligible magnetic field. We refer to
Section 8.5.3.2 for a discussion of the relation this magnetic field might have to the probability to observe bursts from a Z source.

8.5.3 Timing behaviour

All three branches (HB, NB and FB) are found in the observations, with characteristic types of timing behaviour in each branch. In the next paragraphs we discuss the various power spectral components, VLFN, HFN, LPN and QPO as a function of position in the Z separately.

8.5.3.1 Very-low-frequency noise

The VLFN was detected in all branches. Near the HB/NB vertex its rms was smallest (~0.5%), while in the FB the VLFN was strongest (rms of up to at least ~3%). We found power law indices between ~0.8 and ~2. These results are consistent with VLFN parameters determined from Ginga data on GX 17 + 2 by Penninx et al. (1990).

Several other sources have been investigated in detail for VLFN as a function of $S_Z$ (GX 5–1: Kuulkers et al. 1994a [Chapter 3], EXOSAT argon; Sco X–1: Dieters & van der Klis 1995, EXOSAT xenon, Hertz et al. 1992, Ginga) or as a function of rank number (GX 5–1: Lewin et al. 1992, Ginga, Cyg X–2: Hasinger et al. 1990, Ginga, Hasinger 1993 private communication, Ginga and EXOSAT argon; GX 340 + 0: Van Paradijs et al. 1988a, EXOSAT argon, Penninx et al. 1991, Ginga, Kuulkers & van der Klis 1995b [Chapter 7], EXOSAT argon). Hasinger & van der Klis (1989) investigated EXOSAT data of the six Z-sources as a function of branch. Comparing the EXOSAT argon and the Ginga results for the Z sources (both X-ray instruments have roughly the same energy range), we find that VLFN is lowest in the upper NB, near the HB/NB vertex. This minimum strength is remarkably similar for all the sources: ~0.5%. The increase in VLFN from the upper NB to the lower FB is strongest in GX 5–1 (Kuulkers et al. 1994a, Chapter 3), and probably Cyg X–2 (Hasinger 1993 private communication). The VLFN rms near the NB/FB vertex is ~4% in GX 5–1 (Kuulkers et al. 1994a, Chapter 3), while it is about 2% for GX 340 + 0 (Van Paradijs et al. 1988a, Penninx et al. 1991), GX 17 + 2 (this Chapter) and Sco X–1 (Hertz et al. 1992). The sources GX 5–1 and GX 17 + 2, which have a well developed HB, show evidence for a maximum of ~1% in the middle HB (Kuulkers et al. 1994a [Chapter 3], this Chapter). As shown by Dieters & van der Klis (1995), the VLFN is stronger in the 5–35 keV xenon data (see also Stella et al. 1987), i.e. at higher energies.

The power law indices for GX 340 + 0 (Penninx et al. 1991), GX 17 + 2 (Penninx et al. 1990, this paper) and Sco X–1 (Hertz et al. 1992, Dieters & van der Klis 1995) show more or less the same behaviour as a function of $S_Z$. It is low (~≤1) in the HB and upper NB, while it increase to ~2 near the NB/FB vertex. In the FB VLFN power law indices around 2 have been found (note that the true values could be even higher, due to the leakage of power in the VLFN frequency range). GX 349 + 2 (Hasinger & van der Klis 1989) shows behaviour consistent with this. GX 5–1 (Kuulkers et al. 1994a, Chapter 3) shows a clearly opposite behaviour. The power law index starts at about 2 in the HB to the middle NB, and then drops to ~1.4 in the lower FB.

In the unified model of Lamb (1989) the increase of VLFN from the lower NB into the FB is explained by an instabilities in the accretion flow. When M reaches the Eddington limit radiation pressure becomes important. Accretion onto the neutron star becomes highly unstable at this stage, and therefore increases the VLFN strength.

8.5.3.2 Horizontal branch QPO

In the upper/middle HB we found HBO with frequencies between 24 and 28 Hz, FWHM between 1 and 8 Hz, and rms between 1.5 and 2.5%. These values are similar to those reported by Stella et al. (1987) and Langmeier et al. (1990) for the EXOSAT data. The HBO decrease rapidly in
strength from the upper HB to the middle NB. The range of the HBO frequencies falls within the range (18–30 Hz from upper to lower HB) found by Penninx et al. (1990) in Ginga data. We found evidence for a harmonic, consistent with twice the HBO frequency and similar strength, as was reported by Langmeier et al. (1990).

We note that the sources GX 5–1 (Lewin et al. 1992, Kuulkers et al. 1994a, Chapter 3), Cyg X–2 (Hasinger 1987a, Hasinger et al. 1990) and GX 340+0 (Penninx et al. 1991) show behaviour that is somewhat different from that of GX 17+2; in particular their maximum HBO frequencies are much higher. These sources have HBO frequencies between 15 and 55 Hz, from the left HB (these sources show a horizontal HB in the CD, instead of one that is nearly vertical) to the upper NB, with rms amplitudes between 6 and 2%, respectively. In GX 5–1 a harmonic between 45 and 80 Hz, with rms amplitude roughly half the HBO rms was found (Lewin et al. 1992, Kuulkers et al. 1994a [Chapter 3]); a similar harmonic was also reported in the HBO of GX 340+0 (Kuulkers & van der Klis 1995b, Chapter 7).

The HBO are thought to have a magnetospheric origin (Alpar & Shaham 1985, Lamb et al. 1985, Ghosh & Lamb 1990), where the HBO centroid frequency ($\nu_{\text{HBO}}$) is the beat-frequency between the neutron star spin frequency ($\nu_{\text{NS}}$) and the Kepler frequency of the inner disk edge ($\nu_{K0}$). This model requires inhomogeneities in the accretion flow, which have as a natural consequence the production of LFN. The radius of the inner edge of the disk depends on $M$, the magnetic moment $\mu$ and the mass $M$, of the compact object (Ghosh & Lamb 1992). For n-fold symmetry in the magnetic field pattern, this leads to (see Lamb et al. 1985, Ghosh & Lamb 1992):

$$\nu_{\text{HBO}} = n(CM^a \mu^b M^c - \nu_{\text{NS}}),$$  \hspace{1cm}(8.1)$$

where $n$ is the harmonic number, $C$ is a constant, and $\alpha$, $\beta$ and $\gamma$ are exponents which depend on the particular inner disk model considered; $\alpha > 0$, $\beta < 0$, whereas $\gamma$ can be either positive or negative. There are various ways to produce the ~factor 2 lower HBO frequency range in GX 17+2 as compared to the other $Z$ sources: lower the overall mass-accretion rate, increase the magnetic field strength or the mass of the neutron star, either increase or decrease the spin period of the neutron star depending on the value of $\gamma$ or lower the harmonic number. Of these possibilities, differences in $\alpha$ and $\beta$ are unlikely. $M$ is thought to be the same at the apexes for all $Z$ sources (Lamb 1989, Hasinger et al. 1990), unless the inclination influences the position of the apexes in an unknown way (see also Section 8.5.2). Depending on the value of $\gamma$ (which is probably in the range $-0.6$ to $0.8$) neutron star masses are not likely to be sufficiently different to explain a factor of 2 in the maximum HBO frequency. A closer match between $\nu_{\text{NS}}$ and $\nu_{K0}$ in GX 17+2 than in the other $Z$ sources would of course also lead to a lower QPO frequency. However, in that situation the range in HBO frequency, which is determined by the range in $\nu_{K0}$, would still be expected to be similar to that in the other sources, whereas it is lower: ~12 Hz in GX 17+2 versus ~35 Hz in GX 5–1 and Cyg X–2.

Since the maximum HBO frequency in GX 17+2 is almost a factor of two lower than the maximum HBO frequency in Cyg X–2, GX 5–1 and GX 340+0, we here explore the possibility that the HBO frequency seen in GX 17+2 is dominated by the fundamental (or first harmonic) of the field symmetry ($n=1$) and the HBO frequency seen in the latter sources by the second harmonic ($n=2$). This can be realized if in GX 17+2 the radiation from one magnetic pole at the neutron star surface dominates that from the other magnetic pole, whereas in the other sources both poles contribute approximately the same amount of radiation. The less luminous magnetic pole in GX 17+2 is expected, if its luminosity is not negligible, to give rise to a second harmonic with centroid frequencies in a similar range as the HBO in the other sources, as actually observed in GX 17+2. The harmonic seen in GX 5–1 and GX 340+0 is weak compared to GX 17+2 and in our interpretation due to deviations from the HBO signal from being sinusoidal. If the above described model is right, we predict the presence of a subharmonic (due to the difference between
8.5 Discussion

Figure 8.8. (a) A neutron star (radius 10 km) with a symmetric dipole field. The spherical magnetosphere (indicated by a dotted line) in this plot is taken to be at a radius of 30 km. The last closed field line is indicated with a dashed line. The corresponding accretion polar cap on the surface of the neutron star is indicated with a fat line. (b) Same neutron star with a shifted (by 5 km) magnetic dipole field. The upper pole now has a much larger area than the lower pole.

the emission from the two poles) in the power spectra of GX 5–1, Cyg X–2 and GX 340+0, while it should be absent in the power spectra of GX 17+2.

Differences in the radiation from the two magnetic poles could be caused by asymmetries in the field geometry, which lead to different rates of accretion onto, or different emission characteristics from the two poles. These asymmetries would also lead to a difference in the surface area of the two polar caps. Different polar cap areas have also been deduced from pulse analyses in several pulsars (e.g. Leahy 1991, Bulik et al. 1992).

We note that in this situation type I bursts might have a higher chance to occur, as on the larger of the two polar caps accretion per unit area would be less, and therefore on that pole the conditions would be less favourable for steady nuclear burning depleting all fuel than for two equal-area polar caps. Both the presence of bursts and the lower maximum HBO frequency might therefore be explained in this model.

We shall for illustrative purposes consider one simple asymmetry, namely that which arises when the (dipole) magnetic field center does not coincide with the neutron star origin center, but is shifted. In Figs. 8a and b we plotted a magnetic dipole field in which the neutron star center coincides with the magnetic field origin (Fig. 8a) and one in which the neutron star origin is somewhat shifted (Fig. 8b). In these figures we have indicated the polar caps as expected from the last closed field line in a simple dipole plus spherical magnetosphere geometry. It is known that deviations from this geometry will occur, especially near the inner disk edge, because of the magnetic field of the accretion disk (e.g. Ghosh & Lamb 1979, Spruit & Taam 1990), but we ignore this here. We computed the areas of the two polar caps by assuming magnetospheric radii between 15 and 100 km (which is roughly the range expected in Z sources, see Ghosh & Lamb [1992]), and offsets of the magnetosphere origin with respect to the neutron star origin between 0 and 5 km. The neutron star was assumed to have a radius of 10 km. In Table 8.6
Table 8.6: Polar cap areas (km$^2$)$^a$

<table>
<thead>
<tr>
<th>$r_m^b$ (km)</th>
<th>Dipole field offset (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>259 325 389 456 519 591</td>
</tr>
<tr>
<td>259 214 157 109 70 41</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>84 110 140 172 207 245</td>
</tr>
<tr>
<td>84 68 49 33 22 13</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>33 43 55 69 86 106</td>
</tr>
<tr>
<td>33 26 19 13 8 5</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Total area of the neutron star is $\sim$1257 km$^2$.
$^b$r$_m$ is the magnetosphere radius.

we give the results. As can be seen in this table, a slightly offset magnetic dipole field already has a significant effect on the polar cap areas. In particular for small magnetospheric radii, a small offset will cause the larger of the two polar caps to cover a considerable fraction of its hemisphere.

When M increases along the Z, the magnetospheric radius becomes smaller. This leads to a rapid increase in the polar cap areas, which might explain the fact that the four bursts observed with EXOSAT occurred in the NB and FB, and not in the (lower M) HB. However, somewhat dependent on the inner disk model (see Ghosh & Lamb 1992), accretion per unit area may still increase when total M increases in our simple model.

8.5.3.3 Normal and flaring branch QPO

On one occasion we found evidence for FBO with a frequency, FWHM and rms of 16 Hz, 7 Hz and 2%, respectively. Similar FBO in GX 17+2 were reported earlier in Ginga data by Penninx et al. (1990) with frequencies up to 20 Hz and rms up to 3%, but not from EXOSAT data. Sco X–1 is the only other Z source in which similar FBO have been reported (see Dieters & van der Klis 1995, and references therein). These kind of FBO evolve smoothly from the NBO, and therefore probably have a common origin. NBO/FBO are thought to be due to oscillations in the optical depth of the radial flow in the inner disk region (Lamb 1989, Fortner et al. 1989) or due to sound waves in the thick accretion disk (Hasinger 1987b, Alpar et al. 1992).

It was recently suggested that the strength of the NBO oscillations depends on the inclination at which we view the Z sources (Kuulkers & van der Klis 1995a, Chapter 5), stronger NBO/FBO occurring in the lower-inclination sources. The strength of the NBO in the lower NB and the fact that we observe FBO in GX17+2 are in accordance with this.

8.5.3.4 High-frequency noise

We found that in GX 17+2 the HFN shows a decrease as a function of $S_Z$ from the HB to the middle NB from $\sim$5.3% to $\sim$2.5%. From the middle NB to the FB the HFN is more or less constant at a level of $\sim$2.5%. These results are different from the behaviour seen in Sco X–1 (Hertz et al. 1992, Dieters & van der Klis 1995), and probably Cyg X–2 (Hasinger et al. 1990, Hasinger 1993 private communication). There the HFN is reported to decrease from the HB, to
the NB, into the FB. None of these observations were obtained with the EXOSAT ME argon detectors such as our observations. The results from Ginga (Hertz et al. 1992, Hasinger et al. 1990, Hasinger 1993 private communication) indicated values which were typically lower than ~1.5% in the FB. The HFN (which has a hard spectrum) reported by Dieters & van der Klis (1995) was determined from EXOSAT ME xenon data, which comprises a higher effective energy band. It has recently been suggested that some of the HFN seen with EXOSAT is instrumental, up to an rms strength of ~2.3% (0.01-100Hz) in the argon data (Berger & van der Klis 1994). Evidence for this instrumental HFN component in the EXOSAT data of a sample of bright X-ray sources is reported by van der Klis & Kuulkers (1995). This instrumental effect is similar to the values found in the middle NB and FB of GX17+2. Our data are therefore consistent with a decrease in HFN strength from the HB to the FB.

Up to now, the physical origin of the HFN is not known. It seems most likely that it is produced in the inner disk regions close to the neutron star, due to the its high frequencies (van der Klis 1994a).

8.6 Summary

We have found two new X-ray bursts in GX17+2 with durations of ~100 and ~300 s. They were observed to occur ~19 hr after each other. These bursts, together with the bursts observed by Sztajno et al. (1986) all occurred in the NB or in the lower FB, i.e. near Eddington accretion rates. No evidence for regular pulsations are found in the bursts.

The Z pattern in the CD, and probably in the HID, is not changing secularly within several percent. This is in accordance with the division of the Z sources in two groups governed by inclination, in which sources with high inclination (GX 5–1, Cyg X–2 and GX 340+0) show secular variations in their Z pattern, while GX17+2, Sco X–1 and GX 349+2 do not.

We have investigated the various power spectral components as a function of position in the Z, SZ, and placed their properties in the framework of the division in two groups and discussed the hypothesis that this division is due to different viewing geometries. Many power spectral properties fit in this picture, but some issues concerning them still need to be resolved.

We suggest that an asymmetric magnetic field, giving rise to different surface areas and emission characteristics of the magnetic poles at the neutron star surface, may explain the occurrence of bursts in GX17+2, the fact that they were not seen at the lowest accretion rates, the fact that the maximum HBO frequency in GX17+2 is lower about a factor two than the maximum HBO frequency in Cyg X–2, GX 5–1 and GX 340+0 near the HB/NB apex, and the fact that the observed range in HBO frequency in GX17+2 is about a factor of two smaller than that of Cyg X–2 and GX 5–1.

Acknowledgements Stefan Dieters is gratefully acknowledged for his discussions and for comments on earlier versions of this paper.
8.7 HER7: Dead time and Poisson noise

Dead time is a severe problem in X-ray astronomy (e.g. Lewin et al. 1988, van der Klis 1989b). Once an X-ray photon is detected, the detector remains "dead" for a certain or variable time. During this "dead time" the detector is unable to register new incoming X-ray photons. The various dead time processes onboard EXOSAT have been described by Andrews (1984), Andrews & Stella (1985) and Tennant (1987). Within the ME instrument (i.e. the detector, electronics and the OBC) both constant dead time (in non-OBC processed data, such as HTR3 and HTR5 observation modes) and variable dead time (in HTR4 and all HER observation OBC modes) processes occur. When the detector is dead for a fixed amount of time after a photon has been detected, one speaks in terms of fixed dead time. In the case the detector can only register one photon within a given time (or "sample cycle"), the dead time is variable (i.e. depending on when the photon is detected within the sample cycle), and one speaks in terms of variable dead time. Both the fixed and variable dead time processes in EXOSAT are quite well understood (Andrews 1984, Andrews & Stella 1985, Tennant 1987, Berger & van der Klis 1994).

Dead time processes have a recognizable effect to power spectra (see Lewin et al. 1988, van der Klis 1989b). Pure counting noise, in the absence of dead time, has a white power spectrum with, in the case of the Leahy et al. (1983) normalization, an average power of two. This white noise component is called Poisson noise and its level, the Poisson level. The Poisson level is modified by the different dead time processes, i.e. the larger the dead time, the lower the Poisson level (note that in this case the Poisson noise is not white any more). In the case of fixed dead time, the Poisson level can be approximated as follows (van der Klis 1989b, see also Berger & van der Klis 1994):

\[ P_{\text{Poisson}} = 2(1 - \mu \tau_{\text{dead}})^2, \]  

(8.1)

where \( P_{\text{Poisson}} \) is the Poisson level, \( \mu \) the observed count rate, and \( \tau_{\text{dead}} \) the instrumental dead time. Berger & van der Klis (1994) determined \( \tau_{\text{dead}} \) to be \( \sim 10.6 \) for the EXOSAT ME argon data from an analysis of the high time resolution data (HTR3, HTR5) of several bright sources. When analysing power spectra of the HTR3 and HTR5 data we determined the Poisson level using Eq. 1.

In the case of variable dead time, the Poisson level is approximated as follows (e.g. van der Klis 1989b):

\[ P_{\text{Poisson}} = 2(1 - \mu \tau_{\text{sample}}), \]  

(8.2)

where \( \tau_{\text{sample}} \) is the duration of the sample cycle, i.e. the effective sampling time. \( \tau_{\text{sample}} \) was reported to be \( 1/3569 \) s by Andrews & Stella (1985) for EXOSAT OBC processed data. Recently, however, it was found by Kuulkers et al. (1994a, Chapter 3) for high observed count rates (1500–2300 cts s\(^{-1}\)) in the OBC processed HER7 data the fitted Poisson levels deviated from that expected from Eq. 2. Since the HER7 data of GX17+2 provided lower count rates (0–1500 cts s\(^{-1}\)), we decided to analyse all four-channel HER7 data for the brightest LMXBs, i.e. Sco X–1, GX 5–1, Cyg X–2, GX 17+2 and GX 3+1. The former four sources are all Z-sources, while the latter is an atoll source (see e.g. Hasinger & van der Klis 1989). In Table 8.A1, we give an observation log of the four channel HER7 argon observations of these sources. We selected the power spectra according to observed intensity and determined the Poisson level by fitting the power spectra with the various source components as described in Sect. 8.4.2.2, with the Poisson level as a free parameter. This was done for each source individually. The results are given in Fig. 8.9. In this figure we also plotted the Poisson levels as predicted from the linear relation Eq. 2. It is clear that the fitted Poisson levels deviate from those expected (especially at high count rates), as was already found by Kuulkers et al. (1994a, Chapter 3). It can be seen that the Poisson level deviations from the predicted linear relation in the various sources where
8.7 HER7: Dead time and Poisson noise

Figure 8.9. Observed Poisson levels for the power spectra of HER7 data for several LMXBs as a function of the raw observed count rate. The HTR4 data of GX 17+2 have also been plotted. The observed Poisson level was determined by adding it as an extra component in the power spectral fits. The different symbols refer to the different sources as indicated. Error bars are on the order of the symbol sizes. The predicted Poisson levels (straight line) and the quadratic fit (dashed line) are included in the plot.

As mentioned in Section 8.3, we rebinned the HTR4 data into a time resolution of ~4 ms, i.e. similar to most of the HER7 data. In the power spectral fits of the HTR4 data the Poisson level was also taken to be a free parameter. The results of these Poisson level fits are also plotted in Fig. As can be seen in this figure, the HTR4 data fall along the HER7 data points, as expected from the fact that these data are processed in a similar way by the OBC as the HER7 data.

Although a linear deviation was sufficient to describe the GX 5–1 data of Kuulkers et al. (1994a, Chapter 3), they found that the Poisson level could also be described as a quadratic function of observed intensity. Here we find that our data are described better by a quadratic function. When fitting the data to such a function, the Poisson level as a function of observed intensity, \( \mu \), is as follows:

\[
P_{\text{Poisson HER7}} = 1.9959(19) - 5.89(4) \cdot 10^{-4} \mu + 3.04(13) \cdot 10^{-8} \mu^2,
\]

where we give the uncertainty in the last digit(s) between brackets. The fitted Poisson levels
Table 8.A1: EXOSAT Argon HER7 observation log

<table>
<thead>
<tr>
<th>Source</th>
<th>Year</th>
<th>Date</th>
<th>Day(^a)</th>
<th>Time Resolution</th>
<th>Spectral State</th>
</tr>
</thead>
<tbody>
<tr>
<td>GX 5-1</td>
<td>1985</td>
<td>Aug 27/28</td>
<td>239/240</td>
<td>3.9 ms</td>
<td>NB/FB</td>
</tr>
<tr>
<td></td>
<td>1985</td>
<td>Aug 29</td>
<td>241</td>
<td>3.9 ms</td>
<td>NB</td>
</tr>
<tr>
<td></td>
<td>1985</td>
<td>Aug 30</td>
<td>242</td>
<td>3.9 ms</td>
<td>NB</td>
</tr>
<tr>
<td></td>
<td>1985</td>
<td>Sep 17</td>
<td>260</td>
<td>3.9 ms</td>
<td>HB</td>
</tr>
<tr>
<td>Cyg X-2</td>
<td>1985</td>
<td>Oct 28/29</td>
<td>301/302</td>
<td>3.9 ms</td>
<td>HB</td>
</tr>
<tr>
<td></td>
<td>1985</td>
<td>Oct 29</td>
<td>302</td>
<td>3.9 ms</td>
<td>HB</td>
</tr>
<tr>
<td></td>
<td>1985</td>
<td>Nov 14/15</td>
<td>318/319</td>
<td>3.9 ms</td>
<td>NB/FB</td>
</tr>
<tr>
<td>GX 17+2</td>
<td>1986</td>
<td>Apr 3/4</td>
<td>093/094</td>
<td>7.8 ms</td>
<td>NB/FB</td>
</tr>
<tr>
<td>Sco X-1</td>
<td>1985</td>
<td>Aug 24</td>
<td>236</td>
<td>3.9 ms</td>
<td>FB</td>
</tr>
<tr>
<td></td>
<td>1985</td>
<td>Aug 25</td>
<td>237</td>
<td>3.9 ms</td>
<td>NB/FB</td>
</tr>
<tr>
<td></td>
<td>1986</td>
<td>Mar 11/12</td>
<td>070/071</td>
<td>7.8 ms</td>
<td>HB/NB</td>
</tr>
<tr>
<td></td>
<td>1986</td>
<td>Mar 13/14</td>
<td>072/073</td>
<td>3.9/7.8 ms</td>
<td>NB</td>
</tr>
<tr>
<td>GX 3+1</td>
<td>1985</td>
<td>Sep 4</td>
<td>247</td>
<td>3.9 ms</td>
<td>UB(^b)</td>
</tr>
</tbody>
</table>

\(^a\)Jan 1 = day 1.
\(^b\)UB = upper banana (see Hainger & van der Klis 1989).

in the observed count rate range 100–900 cts s\(^{-1}\) are below the expected Poisson levels. This is consistent with a previous study by Rutledge (1993 private communication) from HER7 data of the Rapid Burster.

Additional dead time effects have already been discussed by Andrews & Stella (1985) and Tennant (1987). They showed analytical corrections to pure variable dead time effects as described above. Both papers gave expressions for the dead time corrections (Andrews & Stella 1985, Tennant 1987), and estimations for the expected Poisson level (Tennant 1987). One disadvantage, however, is the need to know the incident count rate, which can only be determined from the Qualified Event rate (QE). Since the QE is only sampled every 32s, this approach will only lead to an approximate correction if the source varies largely within these 32 s; such rapid variability is common for Z sources. We therefore approached the Poisson level problem in an empirical way, and fitted the determined Poisson levels to an expanded version of Eq. 2 in \(\mu\tau_{\text{sample}}\), i.e.

\[
P_{\text{Poiss, HER7}} = 2 \left( 1 - \mu \tau_{\text{sample}} + a(\mu \tau_{\text{sample}})^2 \right). \tag{8.4}
\]

This equation still fulfills the requirement that for the observed count rate \(\mu \rightarrow 0\) the expected Poisson level approaches two (dead time is not in evidence at sufficiently low count rate). With \(\tau_{\text{sample}}\) fixed at 1/3569 s, the fit was unacceptable, i.e. \(\chi^2_{\text{red}}\) of 7.2 for 73 dof. When \(\tau_{\text{sample}}\) was set free the fit became good (\(\chi^2_{\text{red}}=1.0\) for 72 dof), with \(\tau_{\text{sample}}=1/3360\) s and \(a=0.18\).

We note that it was possible to fit the data to the function

\[
P_{\text{Poiss, HER7}} = 2 \left( 1 + \sum_{i=0}^{n} (-1)^i \frac{1}{i^2}(\mu \tau_{\text{sample}})^i \right). \tag{8.5}
\]

We found that \(\chi^2_{\text{red}}\) was \(\lesssim 1.0\) for \(n=4\). In that case \(\tau_{\text{sample}}\) was found to be 1/3304 s.