EXOSAT observations of Z sources
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Introduction

Early X-ray astronomy

Almost 70 years after X-rays were first detected by Röntgen in 1895 (see e.g. Tucker & Giacconi 1985), the first extra-solar X-ray source was discovered from a rocket flight by the American Science and Engineering group and MIT led by Giacconi in 1962 (Giacconi et al. 1962). This X-ray star was located in the constellation of Scorpius, and later named ScoX-1 (the “1” designates the source being the first detected in Scorpius; it is also the strongest source in this constellation). It was soon recognized that binary stars could emit X-rays (Hayakawa & Matsuoka 1963), probably through accretion onto a compact star (Salpeter 1964, Zeldovich 1964, see also Zeldovich & Shakura 1969). The suggestion that ScoX-1 itself might be a binary system came from Shklovskii in 1967. Observational evidence for the binary nature came several years later. Radial velocity measurements of the counterpart of another X-ray star, CygX-1, revealed the binary period to be ~5.6 days (Bolton 1971, 1972, Webster & Murdin 1972), while the source CenX-3 was shown to have a ~2.1 day orbital period from X-ray observations with Uhuru (Schreier et al. 1972). ScoX-1 was eventually also confirmed to be a binary system with an optical period of ~0.78 days (Gottlieb et al. 1975). For excellent reviews of the developments during this exciting first decade of X-ray astronomy I refer to the overviews given by Lewin (1994), van den Heuvel (1994), and Trimble (1994), Van Paradijs (1995a), and to the introduction to X-ray astronomy given by Tucker & Giacconi (1985).

Two categories of X-ray Binaries

Further studies showed that the differences in the characteristic behaviour of the (binary) X-ray sources are (partly) due to the nature of the compact object. Today one recognizes several kinds of X-ray binaries, for example X-ray pulsars (such as CenX-3), X-ray binaries containing low-magnetic field neutron stars (such as ScoX-1), and black-hole binaries (such as CygX-1). Another division of the X-ray binaries into two categories is by the mass of the companion to the compact star, i.e. low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs). Companions in LMXBs have masses lower than about one solar mass, whereas companions in HMXBs generally have masses higher than about ten solar masses.

Generally, HMXBs show accretion through a wind (e.g. VelaX-1); only in some of them an accretion disk can form (e.g. CenX-3). Most of the HMXBs show regular X-ray pulses (see e.g. the review of Nagase [1989]), due to the fact that they contain neutron stars with high magnetic fields (B~10^{12} G). In these cases the accretion only takes place onto small areas of the neutron star near to the magnetic poles, due to funneling of the matter by the magnetic field. Periodic modulation is caused by rotation of the resulting hot spots on the neutron star surface into and out of sight of the observer (the magnetic field axis is inclined with respect to the rotation axis of the neutron star).

In LMXBs mass flows from a Roche-lobe filling companion, through an accretion disk, onto the compact object. Most of these systems do not show X-ray pulsations. Instead, many LMXBs show X-ray bursts (see e.g. Lewin et al. 1993). The absence of X-ray pulses and the presence of
X-ray bursts indicate that the magnetic field strength of neutron stars in most LMXBs is lower than of X-ray pulsars (typically, $B \lesssim 10^{10}$ G). Because massive stars live much shorter than low mass stars, LMXBs are thought to be generally older ($\gtrsim 10^9$ yr) than HMXBs ($\lesssim 10^7$ yr).

Low-mass X-ray Binaries

Various types of sources belong to the class of the LMXBs. These include the persistent and transient black-hole candidates (see e.g. Tanaka & Lewin 1995), persistent and transient burst sources, (see e.g. Lewin et al. 1993), bright bulge sources (such as Sco X–1), X-ray dip sources (see e.g. Parmar & White 1988), and some X-ray pulsars (such as GX 1+4). A few LMXBs show unique properties, not detected in any other source. Examples are the Rapid Burster (see e.g. Lewin et al. 1993), and Cir X–1 (see e.g. Oosterbroek et al. 1995).

LMXBs contain either main sequence companions which transfer mass at a low rate due to shrinking of the orbit caused by gravitational radiation and/or magnetic braking, or they have slightly evolved companions which transfer mass at a generally higher rate due to their evolutionary expansion (see e.g. Verbunt & van den Heuvel 1995). These differences in the type of companion are thought to affect the luminosity of the LMXBs, being on average higher in the latter (evolved companion) case. These different types of companions lead to orbital periods that are also different, longer than about half a day in the LMXBs with evolved companions, and shorter than half a day in the LMXBs with main sequence companions. For example, Cyg X–2 has an orbital period of $\sim 9.8$ d (Cowley et al. 1979), so probably contains an evolved companion, while 4U 1636–36 has an orbital period of $\sim 3.8$ hr (Pedersen et al. 1981), showing it to probably contain a main sequence companion (see also Van Paradijs 1995b). Regular X-ray bursts are most often found in the lower luminosity low-magnetic field neutron star sources. The mass accretion rate is thought to govern the occurrence of bursts (see Lewin et al. 1993). At low accretion rates nuclear fuel can accumulate on the neutron star surface so that thermo-nuclear runaways can occur, the so-called type I bursts (see Hoffman et al. 1978; the so-called type II bursts are believed to originate from accretion disk instabilities). At high accretion rates matter is stably burning at the neutron star surface, and no bursts are expected. However, some high luminosity sources still show (irregular) X-ray bursts, such as GX 17+2 and Cyg X–2, as I will show in more detail in this thesis.

Since the magnetic field is weak in the non-pulsating LMXBs, the accretion disk may extend close to the neutron star (e.g. Ghosh & Lamb 1992). Torques exerted by the accreting matter on the neutron star are then expected to spin the star up to millisecond rotation rates (especially at high accretion rates). It was noted that radio pulsars with millisecond spin periods also have magnetic fields in the order of $10^8$–$10^{10}$ G; for this reason they are thought to be produced in LMXBs by spin-up of the neutron star by accretion torques (see e.g. Bhattacharya & van den Heuvel 1991). Many efforts have been made to search for millisecond spin rates in LMXBs, however up to now none have been found in these systems (see e.g. Vaughan et al. 1994b).

Atoll sources and Z sources

Although various types of low-mass X-ray binaries revealed their nature before 1985, in particular by showing pulses, bursts, but also by binary orbital phenomena such as eclipses and periodic ‘dips’, no such clear systematic behaviour could be found in the brightest persistent LMXBs (which we now know contain low-magnetic field neutron star binaries). These sources did not show any good diagnostics; despite their brightness their nature remained unclear for two decades after their discovery. In their search for millisecond pulsations with the European X-ray satellite EXOSAT van der Klis et al. (1985a,b) detected another kind of behaviour which opened up a new
window into these systems. Instead of regular oscillations they found quasi-periodic oscillations (called QPO), i.e. “almost” regular oscillations\(^1\) in one of the brightest persistent LMXBs, GX 5–1 (see Fig. 1). When fast Fourier transforms are used to analyse the light curves on subsecond time scales, the QPO showed up as a broad peak between 20 and 50 Hz in the power spectra (strength or power of a signal at a given frequency; see Section ‘Fourier analysis’ on page x) of the X-ray brightness variations. Soon thereafter several of the other bright persistent LMXBs were also found to exhibit QPO in the range 5–60 Hz (e.g. in Cyg X–2 by Hasinger et al. [1986] and in Sco X–1 by Priedhorsky et al. [1986], see also van der Klis [1989a]). Besides QPO, other well-defined types of variability became recognized in these sources, such as band-limited noise and power law noise (see e.g. van der Klis 1995a). Given the fact that the QPO and the noise components occur on short time scales these components originate most likely in the inner disk regions of these systems.

Another approach to the study of the low-magnetic field neutron star systems was analysis of the broad-band X-ray spectra. Due to instrumental limitations most X-ray spectra obtained up to about 1990 were of relatively poor energy resolution. It turned out that a useful way of analysing such spectra was to divide the spectrum into several broad energy bands and to investigate how the X-ray colour (the ratio of the count rates in two different energy bands) correlated with the “intensity” (count rate) of the source (in so-called colour [or hardness] versus intensity diagrams, or HIDs). It was found that the systems show several different states characterized by correlated behaviour of the X-ray colours as well as of the rapid time variability (see e.g. van der Klis 1989a). Due to the availability of long uninterrupted observations from EXOSAT, it was possible to track the sources on time scales of hours to days and to observe their state change.

Using EXOSAT data for 16 LMXBs Hasinger & van der Klis (1989) used so-called colour-colour diagrams (CDs) to study their broad-band spectral behaviour. In such diagrams (comparable to the optical U–B vs. B–V diagrams) a “soft” colour (ratio of the count rates in the

\(^{1}\)QPO may for example be produced by an oscillation with a constant frequency and a limited duration (i.e. an oscillating “shot”), or by a continuous oscillation with a variable frequency.
Figure 2. X-ray colour-colour (top) and power spectra (bottom) typical of Z sources (left) and atoll sources (right). The direction in which M is inferred to increase is indicated by arrows in the colour-colour diagrams (Hasinger & van der Klis 1989).

lowest energy bands) is plotted versus a “hard” colour (ratio of the count rates in the highest energy bands). From these CDs a pattern in the behaviour of the their sample of LMXBs emerged: the brightest LMXBs followed different kinds of tracks in the CDs with respect to the lower luminosity LMXBs (mostly burst sources). Six of the brightest showed roughly Z-like shaped tracks (or parts of it), while the other sources showed somewhat more fragmented CDs (see top panel of Fig. 2). Because of the shape of these tracks the former sources were named the “Z sources”, while the latter were named “atoll sources”. Z sources show three kinds of states (corresponding to the three limbs of the Z), designated as the horizontal branch (HB, top part of the Z), normal branch (NB, middle part of the Z), and the flaring branch state (FB, lower part of the Z). These names are merely historical (see e.g. van der Klis 1989a) and were based on the fact that in the first few sources studied the horizontal branch showed up as a horizontally oriented limb in the HIDs, the normal branch as a state in which the sources were most of their time, while in the flaring branch the sources showed intensity flares. Atoll sources showed two kind of branches; one was a “banana” shaped (curved) branch, while the other was the “island” state, in which the colours did not change much on a time scale
of hours to days. The occurrence of the different states of the Z sources and the atoll sources is governed by the mass accretion rate. In the Z sources the mass accretion rate increases from the HB, through the NB, to the FB (Hasinger et al. 1990, Vrtilek et al. 1990), while in atoll sources the mass accretion rate increases from the island state, through the lower banana to the upper banana (see e.g. Corbet et al. 1989).

It was shown by Hasinger & van der Klis (1989) that each state or branch has characteristic fast timing variability, and is therefore an extra diagnostic to identify the source state (see e.g. Fig. 2), and to distinguish the Z sources from the atoll sources. In fact, it was only by using this extra diagnostic in conjunction with the CDs that Hasinger & van der Klis (1989) were able to sort out the differences between Z and atoll sources and their various states; from just the spectral data, without the fast timing, this was not possible (see e.g. Schulz et al. 1989). The division of the bright LMXBs into Z and atoll sources was proposed to be due to differences in both the magnetic field and the mass accretion rate (Hasinger & van der Klis 1989). The Z sources are thought to have somewhat higher magnetic fields \(10^8-10^{10} \text{G}\) than atoll sources \(10^8-10^9 \text{G}\) and probably accrete mass at near-Eddington rates (e.g. Lamb 1989), while the mass accretion is well below Eddington rates in the atoll sources. So, the study of broad band spectral and correlated timing behaviour turned out to be a powerful tool to probe the nature of the brightest LMXBs (see also Section 'The tools' on page x). This tool is nowadays also used to study the behaviour of the other X-ray binaries, e.g. the X-ray pulsars and the black hole binaries (see e.g. Van der Klis 1994a,b, 1995a,b,c,d). An overall comparison of these various types of sources shows that there are similarities in the fast timing behaviour. The properties of the rapid fluctuations appear to depend on the magnetic field, the mass accretion rate and the type of the compact object.

On the basis of a thorough study of the correlation between broad-band spectral and fast timing behaviour, I will defend the view, that apart from the magnetic field and the mass accretion rate, inclination also plays a key role in understanding the properties of Z sources.

The Z sources in more detail

X-ray investigations of the Z sources with EXOSAT and the Japanese Ginga satellite have been very fruitful. Each limb of the Z has been studied in terms of CDs, HIDs and correlated fast timing properties. However, most of the work up to now has been very fragmentary. The various properties which showed up in individual Z sources in particular states were assumed, rather than demonstrated, to be also present in other sources. Moreover, comparisons between Z sources were rare and only sketched the broad outlines of the systematics in the phenomenology (Hasinger et al. 1989, Hasinger & van der Klis 1989). The general framework as it emerged from these studies is given in this section.

The Z sources move smoothly, but stochastically through the Z, never jumping from branch to branch. The power spectral components vary with the motion of the sources through the Z. In the next sections I describe the three branches by giving the characteristic behaviour of Z sources in each of them and by discussing (some) of the models proposed for this behaviour. A model to explain the overall behaviour of Z sources is the so-called unified model of Lamb (1989). This model tries to explain all observed properties within the framework of a sequence of inner disk states, governed by the mass accretion rate.

The horizontal branch

Four Z sources show well-developed HBs (GX 5–1, Cyg X–2, GX 340+0 and GX 17+2), while one Z source, Sco X–1, shows a short HB. The sixth Z source, GX 349+2, has never been observed in the HB. In the HB the X-ray intensity increases when the source moves towards the NB. The
branch is observed to appear with different orientations in the CD. Several components can be recognized in the power spectra, see e.g. Fig. 2.

First, in all the sources with a well-developed HB, one observes QPO (called horizontal branch QPO, or HBO, see e.g. Fig. 1a) between ~15 and ~55 Hz. The strength of these QPO decreases as the source moves towards the NB, but they only vanish when the source has already moved into the upper NB. The frequency of the HBO increases from the left HB to the NB, i.e., in correlation with the mass accretion rate; there is no evidence for a further increase once the source has entered the NB. In the upper NB the HBO are sometimes seen simultaneously with another type of QPO (the NBO, see next paragraph). In the left HB harmonics of the HBO are sometimes detected at twice the frequency of the HBO. These harmonics can be as strong as the HBO themselves.

When a Z source is in the HB a band-limited noise component is observed together with the HBO. It extends in the power spectra from ~1 Hz to above the HBO frequency and is called low-frequency noise, or LFN. The presence of the LFN correlates with that of the HBO: they appear and disappear together. LFN has different shapes in different Z sources, i.e. peaked in GX 17+2 and Sco X–1, and non-peaked in GX 5–1, Cyg X–2 and GX 340+0 (noise components are called peaked when they show a local maximum in the power spectrum, and non-peaked when they have their maximum at zero frequency).

Two other noise components are observed, which appear to be present in all three spectral branches. One is a power law component, which dominates the region below ~1 Hz; the other component is similar in shape to the LFN, and dominates the region above HBO frequencies. The former noise component is called very-low frequency noise (VLFN), while the latter is called high-frequency noise (HFN). In the HB, neither component shows a clear dependence on the mass accretion rate, such as the LFN and the HBO. However, from branch to branch (HB-NB-FB) the VLFN increases, while the HFN probably decreases (Hasinger & van der Klis 1989).

Since the occurrence of HBO and LFN are closely coupled, they are thought to arise from the same process. After the discovery of the HBO, a model was put forward which explained them in terms of modulated accretion onto the surface of the neutron star (Alpar & Shalam 1985, Lamb et al. 1985). A magnetic field is thought to dominate the mass flow onto the neutron star. In the inner disk clumps of matter rotate around the neutron star at the Kepler period. Each time a clump crosses a region of the small (typically 15–100 km in radius) magnetosphere where accretion is easy (most likely, a magnetic pole), material enters the magnetosphere and accretes onto the neutron star. This gives rise to intensity variations that have a frequency equal to the beat frequency between the Kepler frequency of the clumps orbiting in the inner disk and the neutron star spin frequency. This model is therefore known as the beat-frequency model. The LFN arises from the accretion of the clumps themselves. As the mass accretion increases the magnetosphere is compressed. The disk then extends to closer to the neutron star, and clumps in the inner disk rotate with shorter Kepler periods. This causes the beat frequency, i.e. the HBO frequency to increase, as observed when a Z source moves towards the NB. In this thesis I explore in more detail some consequences of this beat-frequency model, and show how differences in magnetospheric geometry may explain some of the observed peculiarities of the HBO.

Note, that when the mass accretion rate would be lower than observed in the HB, the magnetosphere would extend to larger radii, which would reduce the size of the polar caps onto which accretion takes place. Moreover, at such low mass accretion rates the neutron star is expected to become less obscured by the accretion flow. For these reasons, pulsations are expected to become visible in Z sources at low mass accretion rates (see van der Klis 1991).

HBO and LFN have hard X-ray spectra, i.e. their strength increases with photon energy.
The HBO at higher energies lag those at lower energies by a few milliseconds ("hard lags", see e.g. Vaughan et al. 1994a). The LFN shows "soft lags". Models in which harder (higher energies) photons have undergone more scatterings than the softer (lower energies) photons in a Comptonised cloud have been proposed to explain the observed lags in the HBO. However, the lags in the harmonic are inconsistent with this picture (Vaughan et al. 1994a).

The normal branch

All Z sources have been found to exhibit a NB. Only in the case of GX 349+2 the full NB (all the way up to the HB) has not been seen.

When the HBO (previous paragraph) start to diminish, in the upper NB, another QPO peak (the NBO) appears. Since the HBO and NBO have been observed simultaneously, they are different phenomena, likely produced by different mechanisms. The NBO show frequencies between 5 and 7Hz, and exhibit a stable frequency along the NB. In the sources Sco X–1 and GX 17+2 the NBO persist into the FB (see next paragraph, in the FB these QPO are called FBO). The fact that the NBO change smoothly into the FBO (see Dieters & van der Klis 1995) suggest that they have the same origin.

The strength of the NBO changes as a function of photon energy. In all sources the strength increases from ~5 up to ~20keV. In Cyg X–2 and GX5–1, however, it shows a minimum so that below a certain energy it increases towards lower energies. In Cyg X–2 this minimum is around 6 keV (Mitsuda & Dotani 1989), while in GX 5–1 it is located near 3.5 keV (Vaughan et al. 1995). The NBO in Cyg X–2 and GX5–1 at energies above the minimum are out of phase with the NBO at energies below the minimum. This is interpreted in terms of a quasiperiodic "rocking" motion of the X-ray spectrum around the energy corresponding to the minimum and can be caused by quasiperiodic variations in the Compton scattering depth of material around the neutron star. In this thesis I present the results of a search for similar phase lags in Sco X–1, which, surprisingly, are absent, and investigate whether the mass accretion rate influences the phase lag spectrum and the rms spectrum of Cyg X–2.

The fact that the NBO frequency does not change much as a Z source moves along the NB may be due to the small change in mass accretion rate along this branch. It is thought to be at near-Eddington values along the entire branch (Lamb 1989). When the accretion rate approaches the Eddington limit, effects of the radiation on the inner disk (radiation pressure, photon drag) become very important, and at least part of the mass fed to the neutron star is thought to come in through a more radially directed flow. Oscillations may occur in this flow due to feedback between accretion rate and X-ray production (Fortner et al. 1989), or alternatively sound waves in a thick accretion disk (Hasinger 1987b, Alpar et al. 1992) may be the origin of the NBO.

In the upper NB some LFN is still visible, but it decreases in prominence hand in hand with the HBO. The VLFN is stronger as compared to that in the HB, and increases toward the FB. HFN has also been reported to be present in this branch; it is weaker than in the HB.

The flaring branch

The FB shows very different types of behaviour in the CD and HID, when one compares the Z sources with each other. As the Z sources move into the FB, the intensity starts to increase rapidly in Sco X–1, GX 17+2 and GX 349+2. These sources show strong flares in intensity corresponding to rapid movements along the FB. However, in Cyg X–2 and GX 340+0 the FBs are not well developed, and the intensity actually starts to decrease at some point in the lower or middle FB. In this thesis I describe the first detection of a small FB in GX 5–1, which shows a similar behaviour as the FB of Cyg X–2 and GX 340+0.
Since the intensity changes rapidly in the FB, the VLFN becomes stronger in this branch with respect to the NB. It increases rapidly up the FB.

In the sources Sco X–1 and GX 17+2 QPO are seen in the lower FB, whose frequency connects smoothly with the NBO. The frequency starts to increase when these sources move into the FB, from the ~6 Hz characteristic of NBO up to ~20 Hz. Soon, when still in the lower FB, the FBO become very broad and vanish into the noise. No FBO have been reported from the other Z sources. Since the FBO are closely connected to the NBO they probably arise from a related process. When a Z source reaches the FB, the mass accretion rate is thought to become super-Eddington. At this stage the radial inflow of matter becomes unstable and photohydrodynamic oscillations may be excited which cause the FBO (see e.g. Lamb 1989).

In this thesis I report the detection of a different type of QPO in the FB of Cyg X–2, which I conclude is unconnected to either NBO/FBO or HBO. These new QPO are thought to show up only in special situations, as will be described in Chapter 5.

Inclination effects?

As noted in several of the previous paragraphs, different Z sources show differences in the same phenomena. The LFN can appear either as a peaked or as a non-peaked noise component, the orientation of the HB in the CD can be different, FBO can be present or absent, increases (flares) or decreases (dips) in intensity can occur when a source moves up the FB (see Hasinger & van der Klis 1989 and references therein). Even in the same source (Cyg X–2) the shape and position of the Z pattern in the CD and HID can show changes (Vrtilek et al. 1986, Hasinger 1987a, Hasinger et al. 1990), see e.g. Fig. 3. Van der Klis et al. (1987b) discussed the importance of inclination in Z sources in the context of an inner disk that becomes puffed up. Sco X–1 has a vertical HB, peaked LFN and flares in the FB, while Cyg X–2 has a horizontal HB, non-peaked LFN and dips in the FB. It was suggested that viewing angle (or inclination) is the origin of the differences (Hasinger et al. 1989, Hasinger & van der Klis 1989). The inclination at which we view a source can be determined from optical observations. This has presently only been possible for Cyg X–2 (65–75°) and Sco X–1 (15–40°), since the other Z sources are in the galactic bulge (see Fig. 4) and severely reddened (see e.g. Van Paradijs & McClintock 1995). Note, however, that the optical counterpart of GX 349+2 has recently been identified (Penninx & Augusteijn 1991). Investigations that may yield information on its viewing geometry are in progress.

As the inner accretion disk becomes radiation pressure dominated in the NB and FB, the disk may thicken. As the disk “puffs up” it might reach a height at which the central region becomes obscured to an observer on Earth, when the system is viewed edge-on (high inclination). This will cause the intensity to drop when the accretion rate increases and the source moves up into the FB. When the system is viewed towards pole-on (low inclination) no obscuration occurs, thus the intensity increases when the mass accretion rate does. The X-ray behaviour thus indicates that Cyg X–2 is viewed more edge-on, while Sco X–1 is viewed more pole-on, consistent with the optical observations.

Since GX 5–1 and GX 340+0 showed similar X-ray behaviour to Cyg X–2, whereas GX 17+2 and GX 349+2 showed similar X-ray behaviour to Sco X–1 (see previous and present sections), Hasinger & van der Klis (1989) proposed that the Z sources could be divided into two subclasses. In this thesis I identify new source characteristics that appear to be in accordance with this subdivision into two groups. I show that several of the properties that are different between the two groups are consistent with the idea that a difference in inclination is the cause of the subdivision.
The tools

Colour-colour diagrams and hardness-intensity diagrams

The changes in the X-ray spectra of the Z sources between the different branches are subtle (see e.g. van der Klis 1994b). As mentioned in Section ‘Atoll sources and Z sources’ on page ii, they are studied by investigating changes in the count rates in broad energy bands. The X-ray spectral data are divided up into three or four bands. The hardness ratio of the count rates in two lowest bands provides the so-called “soft” colour, while the hardness ratio of the count rates in two highest bands provides the so-called “hard” colour. The total count rate of a source in a certain energy band, normally covering the same range as the bands used to calculate the colours is by X-ray astronomical convention called the X-ray “intensity”. One may construct colour-colour diagrams (CDs) and hardness-intensity diagrams (HIDs). In the CD the hard colour is plotted versus the soft colour, in a HID one of the colours is plotted versus intensity.

It has not (yet) been possible to describe the subtle changes in the X-ray spectra of Z sources...
Figure 4. Distribution of LMXBs in galactic coordinates. The Z sources are indicated. The open circles indicate the position and the maximum luminosity of transient sources. The filled circles indicate the average luminosity of the persistent sources or the minimum luminosity of the transient sources. Data are taken from Van Paradijs (1995b). (From Jongert 1994).

properly by fitting models to the data. Using CDs and HIDs it is possible to study the spectral behaviour without model fits. The advantage of CDs and HIDs is that they are very sensitive to subtle spectral continuum changes. A disadvantage, however, is that it is not possible to make a direct quantitative comparison of the CDs and HIDs produced with different X-ray detectors, due to the differences in the spectral responses. Moreover, systematic effects (such as changes in the detector characteristics) affect these diagrams. Correcting for the spectral response matrix is notoriously difficult. However, I will show how to first order the effects of different spectral responses of X-ray detectors on the CD and HIDs can be estimated. This makes it possible to make comparisons between results from different detectors more quantitative.

**Fourier analysis**

Since at millisecond time resolution X-ray detectors such as EXOSAT and Ginga observe only a few counts (or even less) per time bin even for bright sources such as Z sources, variations on these time scales can not be directly observed, as they are completely dominated by photon counting noise. Large amounts of data must be used to improve the signal to noise. A way to analyse millisecond time variability in such data is Fourier analysis, which provides an estimate of the amplitude of the variability (see van der Klis 1989b) as a function of frequency. Fourier analysis also provides an estimate of the phases of the variability as a function of frequency. Normally one selects for analysis a large number of Fourier spectra which are expected, on the
basis of count rate or position in the Z diagram, to refer to rapid variability with the same characteristics.

To investigate the presence of variations, one uses average power density spectra (or power spectra). Power spectra are determined from the Fourier spectra by taking the square of the absolute value of the Fourier transform and then averaged. The presence of different power spectral components may be estimated by fitting functional shapes (e.g. Lorentzians to represent QPO peaks, power laws for VLFN and cut-off power laws for LFN and HFN) to the power spectra. The strength of a power spectral component is usually reported in terms of the "fractional rms amplitude" of the corresponding fluctuations in the time series. This is the square root of the variance in count rate contributed by the fluctuations (which is in turn equal to the power of the component integrated over its frequency range), divided by the mean count rate. Two different normalizations are used, i.e. the Leahy (et al. 1983) normalization and the squared fractional rms normalization (Belloni & Hasinger 1990, Miyamoto et al. 1991). In the Leahy normalization the expected power of the photon counting noise (Poisson noise) is constant and has a value of 2 (it is however modified by detector dead time effects). The squared fractional rms normalization is obtained from the Leahy normalization by dividing each value in the power spectrum by the total count rate (i.e. source plus background) in counts per second, and then multiplying by the square of the ratio of the total count rate to the source count rate. One can then obtain the rms amplitude as a fraction of the source count rate by simply integrating the power spectrum and taking the square root of the result. A power density spectrum normalized in this way has dimension time and is measured in units of (rms/mean)^2 Hz^-1.

Phase information from the Fourier spectra can be used to look for time or phase lags of the signals in different photon energy bands. To determine phase differences between signals at different energies one uses cross spectral techniques. The time or phase lag plotted as a function of energy is called the time-lag or the phase-lag spectrum. To get an estimate of the rms amplitude of a component in a certain energy band, one uses the power spectrum from data in that energy band. The fractional rms amplitude plotted as a function of energy is called the rms spectrum (see also Section ‘Fourier analysis’ on page x).

Why study Z sources?

Z sources are unique laboratories for various reasons. They form one of the few groups of X-ray binaries which are known to often accrete matter through a disk at near-Eddington rates. Observations have shown that the Z sources contain low magnetic field neutron stars. They therefore provide a laboratory for investigating the interplay between the magnetic field and the inner disk. It is likely that at sub-Eddington accretion rates the magnetic field dominates the fast timing properties, while at Eddington accretion rates effects of the radiation on the flow dominate the observed characteristics. Some aspects of the interaction between the inner disk and the magnetic field can be studied in detail in these sources, providing the observational material for testing inner accretion disk models (see e.g. Ghosh & Lamb 1992). When radiation effects become dominant the disk thickens; accretion is then not solely confined in the orbital plane, but approaches a spherically-symmetric geometry, in which the infall is along radial orbits. By studying objects at different viewing angles one can get an idea of how such radial flows behave.

The well defined states in the Z sources and their characteristic properties in each state, can be compared to properties of other X-ray binaries which differ only in mass accretion rate, magnetic field and/or type of compact object. Intercomparisons between the different X-ray sources help to disentangle the effects of these parameters on the observable properties. This will hopefully lead to a clearer view of the place of Z sources and other X-ray binaries in the framework of binary evolution, and of their links with the millisecond pulsars.
This thesis contains a study of the spectral and corresponding time variability of the Z sources using archival data. Most of the data analyzed in this thesis come from the European satellite EXOSAT. Some data came from the Japanese satellite Ginga. Satellites such as EXOSAT and Ginga are suitable for the analysis of broad-band spectral and fast timing properties since they had collecting areas large enough to provide high signal to noise. Smooth, sharp tracks show clearly the different branches in CDs and HID, whereas count rates are high enough study the rapid variability down to millisecond time resolution.

Parts of the data described in this thesis have been discussed previously by other authors. Such studies were, however, fragmentary, describing only part of the available data on a given source and part of the phenomena present in each data set. Different research groups used different analysis techniques, which made a detailed comparison between different sources impossible. Moreover, most of these early publications occurred before the global picture of the Z sources had emerged from the study of Hasinger & van der Klis (1989), so that the results could not be placed within the general framework. This thesis is the first comprehensive and detailed comparative study of the correlation between broad-band spectral and fast timing behaviour, along each branch, across a sample of Z sources.

We combined all available EXOSAT data on most of the Z sources, and investigated the broad band spectral variations using CDs and HID, and the correlated timing behaviour using power spectra. We paid particular attention to the homogeneity of the analysis, in order to facilitate comparisons between various observations. We performed a comparison between all the Z sources and placed the results within the general framework of mass accretion driven states parametrized by locus in the Z track. Chapters 3 to 9 describe our X-ray studies of GX5–1, Cyg X–2, GX340+0 and GX17+2. The instrument that produced most of the data, the EXOSAT Medium Energy array, is discussed in Chapter 1.

Since various of the effects observed in Z sources are subtle, it was necessary to investigate how instrumental effects could have influenced the observations. X-ray detectors are not ideal detectors and change in the course of a few years. We did a detailed analysis of systematic effects in the CDs and HID, by investigating the position of the Crab Nebula in such diagrams. The Crab Nebula is a constant X-ray source, and therefore its position in the diagrams should not change. If changes occur, they must be attributed to the instrument. This work is presented in Chapter 2.

Fast timing properties are also affected by the detector. Since X-ray detectors can only tag one incoming photon at a time they tend to miss photons that arrive close together in time. Such effects become easily visible at high count rates. Ways to correct for such effects are described in the appendices of Chapter 3 and Chapter 8.