X-ray and radio studies of low-mass X-ray binaries
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Chapter 1

Introduction

1.1 General remarks, history, high- and low-mass X-ray binaries

Preface

In this Chapter I will briefly describe the global properties of the sources which are the subject of this Thesis. After some historical remarks, I will indicate how X-ray binaries have been classified. In particular there are now two recognized subclasses of low-mass X-ray binaries: the Z sources (1.3) and the Atoll sources (1.4). Many atoll sources emit X-ray bursts, for which five studies are presented in Chapter 2. One of the most interesting features of the Z sources are the quasi-periodic oscillations (QPO). Four studies of this phenomenon are presented in Chapter 3. Apart from radiating at X rays, many of these sources can be observed at Ultraviolet (UV), optical, infrared, and radio wavelengths. Some studies of the radio emission of Z sources are presented in Chapter 4. It is not the intention in this introductory chapter to give an exhaustive review with extensive references. Instead, we will refer the reader to some recent reviews for more detailed information.

1.1.1 The birth of X-ray astronomy

X-ray astronomy is a relatively young branch of astronomy. Since X rays are effectively absorbed by the Earth's atmosphere, observations of X rays from space have only become possible with the advent of rockets and balloons that carry instruments to large altitudes. In 1948 the first celestial X rays were observed from the Sun. Several attempts in the 1950's to detect X rays from other celestial sources failed (Friedman 1959). This negative result was not considered very surprising: possible stellar objects, emitting a fraction of their total energy output in X rays comparable to that emitted by our Sun, would give rise to X-ray fluxes which were too low to be detected with the instruments available at that time. The first extra-solar X-ray source (later named Sco X-1) was discovered in June 1962 during a rocket flight aimed at observing the Moon and testing new, sensitive instruments (Giacconi et al. 1962). The existence of such bright X-ray sources was unexpected; this emission could not be of normal stellar origin. In the years following, about 30 bright and highly variable galactic X-ray sources were discovered during rocket and balloon observations. With the first X-ray satellite, Uhuru, launched in 1970, more than 300 sources were discovered. In the 1970's, Uhuru was followed by many other X-ray satellites (Vela-5, Copernicus, Ariel V, ANS, SAS 8, HEAO 1 and Einstein (HEAO 2)). From observations made with these instruments it has become clear that probably all stars in the Galaxy emit X rays, but that in most cases the X-ray
emission constitutes only a very small fraction of the total energy output of the star. The objects studied in this Thesis, however, are bright X-ray sources, which emit most of their energy in X rays. For a more detailed account of the early history of X-ray astronomy, I refer the reader to the book by Tucker and Giacconi (1985).

1.1.2 X-ray binaries

In 1966 a rocket flight with instruments having a high angular resolution provided a position accurate enough (Gursky et al. 1966) to enable the identification of the optical counterpart of Sco X-1 as a 13th magnitude blue star (Sandage et al. 1966). Following earlier work by Zel'dovich (1964), Salpeter (1964) and Hayakawa and Matsuoka (1964), Shklovskii (1967) proposed a model for Sco X-1 in which X rays are produced by mass transfer from a companion star to a neutron star of \( \sim 1 \, M_\odot \). However, the correctness of this model was not established until the discovery of X-ray pulsars with the Uhuru satellite (Giacconi et al. 1971) and of Doppler shifts in the arrival times of the pulses from the X-ray pulsar Cen X-3 (Schreier et al. 1972).

The objects thus discovered are called X-ray binaries. We now know that these X-ray binaries can be divided into two groups, the high-mass and the low-mass X-ray binaries, with the following properties:

1. High-mass X-ray binaries (HMXBs)

These objects consist of a compact object (neutron star or black hole) and a massive (\( \gtrsim 10 \, M_\odot \)) early-type companion star. The HMXBs can be subdivided into two groups; those containing a supergiant, and those containing a Be star (see van den Heuvel and Rappaport 1987). The optical emission is dominated by the massive star. The UV spectrum shows clear evidence for the presence of a stellar wind from the massive companion, which provides the mechanism for the mass transfer to the compact object. The optical light of the mass donor is in general larger than the X-ray flux from the accreting object (typically \( L_\text{x}/L_\text{opt} \leq 1 \) for the galactic HMXBs). In some cases there is evidence that an accretion disk is formed around the compact object. Most high-mass X-ray binaries show regular pulsations in their X-ray flux (see Nagase 1989). These pulsations are caused by the strong magnetic field (\( \sim 10^{12} \) G) of the neutron star, which forces the infalling matter to accrete near the magnetic poles of the star. As a result of a misalignment of the rotation axis and the magnetic axis of the neutron star, a rotating beam of X-ray emission occurs which periodically sweeps past the Earth. The accretion towards the small areas near the poles causes these areas to be extremely hot, which gives hard spectra (in some cases extending to energies up to \( \sim 50 \) keV).

The strength (\( \sim 10^{12} \) Gauss) of the neutron star magnetic fields has been estimated so far in five cases from the energies of synchrotron lines in the X-ray spectrum.

The fact that the mass donor is an early-type massive star, indicates that the high-mass X-ray binaries are relatively young (\( \lesssim 10^7 \) yr). This is consistent with the fact that these objects are concentrated towards the galactic plane and in the Magellanic Clouds, where star formation took place recently.
2. Low-mass X-ray binaries (LMXBs)

In these systems the companion of the compact star is a low-mass ($\lesssim 1 M_\odot$) late-type star. Mass transfer occurs through Roche-lobe overflow and, due to the angular momentum of the transferred matter relative to the compact object, an accretion disk will form around the latter. The emission of the source is dominated by X-rays (typically $L_x/L_{\text{opt}} > 10^2$). The optical emission comes (for most LMXBs) mainly from the accretion disk and is due to reprocessing of X-rays. X-ray pulsations are very rarely observed, which probably indicates that the magnetic field of the compact object is generally weak ($\lesssim 10^8$ G).

The low-mass X-ray binaries are concentrated towards the galactic center. Many have also been found in globular clusters. Their late-type companions and the sky-distribution of these objects suggest that they generally belong to an old galactic population.

Pulsars have been found mainly in HMXBs. It appears that hard X-ray spectra and the presence of pulsations are strongly correlated. This indicates that the absence of pulsars in LMXBs is not caused by alignment of the magnetic axis and the rotation axis but by their having much weaker magnetic fields. Since LMXBs are much older than the HMXBs, this has led to the idea that neutron star magnetic fields in X-ray binaries decay.

1.2 Low-mass X-ray binaries

X-ray studies of LMXBs have shown that these objects can be divided into distinct groups on the basis of their X-ray timing and spectral characteristics. These X-ray characteristics are in most cases related to the properties of the compact object: neutron star or black hole, strength of the magnetic field, the spin period, the angle between spin and magnetic field axes and the mass accretion rate. In some cases the inclination angle of the system influences the observed properties.

Studies over the past few years, culminating in the recent work by Hasinger and van der Klis (HK, 1989), have shown that the persistent bright LMXBs can be divided into two groups, the so-called 'Z sources' and 'atoll sources'. These two groups are different in their X-ray spectral and fast-variability characteristics (see e.g. Section 3.2 for a study of an atoll source). According to HK these differences may be related to a different evolution resulting in differences in the accretion rate, and in the magnetic field of the neutron star.

Several LMXBs have not been classified as Z or atoll sources. White, Kaluzienski and Swank (1983) came to the conclusion that the LMXB transients can also be divided into two classes on the basis of their spectra. Transients are sources which are undetectable for most of the time, then turn on and rise to a maximum in typically a few days and afterwards decay more slowly (time scale of months) into invisibility. White et al. (1983) suggested that the transients with ultrasoft spectra are a separate group of sources, probably containing black holes, while the other sources, with soft spectra, contain neutron stars. Some of the soft (but not ultra-soft) X-ray transients (when active) have emitted regular X-ray bursts, which is quite characteristic for the atoll
1.3 Z sources

It is possible that this second group of LMXB transients belongs to the same class as the atoll sources.

Among the remaining LMXBs are three pulsars, probably containing a neutron star with much stronger magnetic fields than in the atoll and Z sources. The existence of LMXB pulsars was taken as evidence for the occurrence of accretion induced collapse. In this scenario a white dwarf accretes large amounts of mass; once the total mass exceeds the Chandrasekhar limit, the white dwarf collapses and a neutron star is formed; this thus creates the possibility of having a young neutron star (with high magnetic field) in an old system. Recently, Verbunt, Wijers and Burm (1990) have argued that the observational evidence accepted so far for this process is very weak, and they have taken the existence of LMXB pulsars as an argument that magnetic fields do not always decay to very low values.

Some LMXBs behave in a way that is atypical for any of the above-mentioned categories, e.g. the Rapid Burster, Cir X-1, GX 339-4 and Cyg X-3. The Rapid Burster and Cir X-1 show periods in which their timing and spectral behaviour are similar to that of a normal atoll source. However, during other periods their variability is extraordinary. Several remaining LMXBs have not (yet) been classified. In some cases this is due to a limited number of observations; in other cases it is due to a very high inclination angle which hides the central X-ray source from our view (the accretion disk corona sources).

The sources which have been studied for this thesis are Z sources and atoll sources. We will describe these sources in some detail in Sections 1.3 and 1.4 respectively.

1.3 Z sources

1.3.1 The energy spectral and power spectral behaviour of Z sources

The Z sources are so called because they describe a Z-shaped track (or part of a Z-shaped track) in the X-ray ‘hardness-intensity’ and ‘colour-colour’ diagrams (see Fig. 1.3.1). Three branches can be distinguished in these diagrams, which are called the horizontal branch (HB), the normal branch (NB) and the flaring branch (FB). The properties of the power spectra are correlated with these three branches of the Z (Fig. 1.3.1). On the horizontal branch intensity-dependent quasi-periodic oscillations (QPO) and low-frequency noise (LFN) are present. The QPO have central frequencies between 15–55 Hz, increasing in frequency as one moves to the right of the horizontal branch in the hardness-intensity diagram, into the direction of the NB. On the NB QPO are present with a central frequency near ~ 6 Hz. This frequency is independent of the position on the normal branch. On the flaring branch QPO sometimes occur, in which case the central frequency increases from ~ 6 to ~ 20 Hz near the soft end of the soft colour. No LFN is present on the NB or FB. A very-low-frequency noise (VLFN) component with a power-law shape is present on all branches. This VLFN is strongest on the FB, where the power-spectral index of this component is also steepest.

The limited spectral resolution of most X-ray instruments (E/ΔE ~ 9) does not give an accurate determination of the continuum and spectral lines. The spectra of Z sources are well fit by blackbody spectra that are comptonized by a hot electron cloud (Schulz and Wijers 1989).
HK have identified six Z sources: Sco X-1, Cyg X-2, GX 17+2, GX 5-1, GX 340+0, and GX 349+2. The compact objects in these six sources are probably neutron stars: for GX 17+2 X-ray bursts have been observed.

There may be an evolutionary distinction between the Z and atoll sources, with the Z sources consisting of a neutron star and a low-mass giant as mass donor, and the atoll sources having a different type of mass donor. The accretion onto the compact object is determined by the mass loss of the giant, which expands along the giant branch. The X-ray luminosities in the Z sources are likely to be close to the Eddington limit of $\sim 1.4 M_\odot$ neutron star. The UV-luminosities (X-ray heating) and radio luminosities (if available) also appear to be rather similar among the Z sources (see Penninx 1989).

### 1.3.2 Quasi-periodic oscillations

The power spectra of the X-ray intensity variations of Z sources are correlated with the position of the source in the Z-diagram (see e.g. Sections 3.3 and 3.4). In the power spectra one can see one (in some cases two) relatively narrow peaks and various broad noise components. For observational reviews, see Lewin, van Paradijs and van der Klis (1988) and van der Klis (1989); for a review concentrating on theoretical results, see Lamb (1989). HK limit the term QPO presently to two specific kinds of peaks in the power spectra, which are called the horizontal branch oscillations (HBO) and the normal branch oscillations (NBO). All remaining broad peaks and non-peaked components are called ‘noise components’. The shape of the power spectrum is generally fitted with different components to mathematically express its shape. Lorentzian (or sometimes Gaussian) shapes are used for the QPO peaks. This requires three parameters for each QPO component, the central frequency (in Hz), the full width half maximum of the peak (FWHM in Hz), and the fractional rms variation (which is the ratio of amplitude variability in the oscillating signal with respect to the total signal, given in %). The other noise components are represented in various shapes and forms, e.g. Lorentzian shapes (sometimes with a fixed central frequency at 0 Hz), power-laws, cut-off exponentials. For the noise components the variability can also be expressed in terms of fractional rms variation; by integrating the power spectrum for the given mathematical shape between zero and infinity (Hz), or by integrating the observed power spectrum in a certain limited frequency band.

The fractional rms variation in the various QPO and in the noise components in the Z sources is in general between 2–10 %.

Various light curves can produce a broad peak in a power spectrum (see van der Klis et al. 1985 and ref.). Two types of variability in these light curves presently seem good candidates for the origin of the QPOs in LMXBs. The first one is an oscillation with a constant frequency and a limited duration (a ‘shot’), in which the phases of the shots are unrelated. The central frequency is then given by the constant frequency, and the FWHM scales inversely with the duration of the shots. A second way to create a broad peak is by having a continuous oscillation, but a variable frequency. In this case the central frequency is given by the average frequency, and the FWHM is given by the range over which the frequencies drift. It is also possible that a combination of broadening mechanisms is present.
1.3 Z sources

Figure 1.3.1 The X-ray colour-colour diagrams (top) and power spectra (bottom) of the Z sources Cyg X-2 and GX 17+2 (figures taken from HK)

1.3.2.1 Horizontal branch

The discovery of QPO in GX 5-1 was made when the source was on the horizontal branch (van der Klis et al. 1985). The central frequency (between 14-55 Hz) of the QPO correlates with the position of the source on the horizontal branch: as the intensity increases, the central frequency increases. Sometimes a second harmonic is observed, showing that the oscillations are not sinusoidal. These QPO are called horizontal-branch oscillations (HBO). A low-frequency noise (LFN) component, which can not be described by a simple power-law is also present on this branch. The QPO and
LFN components have similar values of the fractional rms variation. The LFN has a maximum contribution to the noise variability in the 1-10 Hz range. In some sources the LFN is peaked near 1-2 Hz. Variability on time scales of minutes along the branch contributes to a very-low-frequency noise (VLFN) component.

The QPO and LFN characteristics on the horizontal branch may be explained by the beat-frequency model (e.g. Alpar and Shaham, 1985; Lamb et al. 1985). In this scenario blobs of accreted material orbit the neutron star at the magnetospheric radius. The QPO frequency is the difference in Kepler frequency at the magnetospheric radius and the spin frequency of the neutron star. The magnetospheric radius depends on the mass accretion rate, which would, according to this model, result in the observed relations between the observed X-ray flux and the observed QPO frequency. This scenario leads to inferred neutron star magnetic fields of $\sim 10^{9-10}$ Gauss, and pulse periods of $\sim 10$ msec. When the source is on the horizontal branch the NBO (see below) are absent.

### 1.3.2.2 Normal and flaring branch

On the normal branch $\sim 5-7$ Hz QPO are present, whose frequency (but not the fractional rms variations) seem independent of position on the normal branch. Apart from these normal-branch oscillations (NBO), a power-law shaped VLFN component is present, representing the movements of the source along the branch. The NBO have fractional rms variations of $\sim 1-5\%$. In some cases weak HBO are detected on (the upper part of) the normal branch, in which case their frequency is equal to that of the maximum frequency on the horizontal branch.

On the flaring branch QPO have been detected in two sources. These QPO are a continuation of the NBO and have the same physical origin: as the source moves from normal branch to flaring branch the frequency starts increasing, up to $\sim 20$ Hz, after which no clear QPO are visible. The increase of flaring activity is represented by an increase of the fractional rms variation of the VLFN. The VLFN power-law shape becomes steeper, shifting the variability from relatively short time scales (less than a second) to longer time scales (greater than minutes).

Lamb (1989 and ref.) proposed that the NBO are caused by oscillations in the optical depth of an approximately spherical symmetric inflow, driven by negative feedback between the accretion rate and X-ray luminosity. An essential element of this model is that the source luminosity should be between 98 and 100 % of the Eddington limit. This may be hard to reconcile with the observations of X-ray bursts from GX 17+2 (Shibazaki 1989).

### 1.3.3 Radiation at other wavelengths

#### 1.3.3.1 The optical light of Z sources

Two of the Z sources, Cyg X-2 and Sco X-1, have optical/UV counterparts: the interstellar absorption to the remaining Z sources is very high which makes them undetectable in the optical passband. The optical/UV emission of Cyg X-2 has contributions from two parts: the optical light of a mass-donor star (with an absorption spectrum) and optical/UV light of reprocessed X rays from the accretion disk (with an emission spectrum). The gravitational energy that is released in the disk is thought to contribute insignifi-
1.3 Z sources

Significantly to the optical/UV light (van Paradijs 1983). Using radial-velocity variations in the optical spectra, orbital periods for Sco X-1 and Cyg X-2 could be determined: they are 0.78 and 9.8 days respectively. For Cyg X-2 the mass donating giant is evolved and is the main source of its optical light (Goranskii and Lyutyi 1965), while in Sco X-1, where the mass donating giant is less evolved, the optical light is dominated by the accretion disk. The difference between the known orbital periods of the atoll sources and Z sources led HK to speculate that Z and atoll sources have giants and main-sequence stars as mass donors, respectively. For a review on orbital periods of LMXBs, see Parmar and White (1988).

Multi-wavelength observations of Cyg X-2 and Sco X-1 show that there exists a general correlation between the optical/UV brightness and the X-ray spectral state. A consensus has developed that this can be understood as a result of an increase of the mass accretion rate as one goes from the horizontal, via the normal to the flaring branch (Hasinger et al. 1990). The X-ray luminosities of the Z sources are near the Eddington limit (\( \sim 10^{38} \) erg s\(^{-1} \)) and the transition from normal to flaring branch is believed to be the transition from sub-Eddington to super-Eddington emission (e.g. Hasinger et al. 1990, Lamb 1989).

1.3.3.2 Radio emission of Z sources

Four of the Z sources have been reported as radio sources (see Hjellming 1988, or Section 4.1 for a review on radio emission from X-ray binaries). The radio emission from X-ray binaries looks like synchrotron emission from ionized clouds with energetic particles (compare e.g. the van der Laan [1966] models, discussed below).

Simultaneous radio/X-ray observations of the Z sources GX 17+2, Cyg X-2 and Sco X-1 have shown that a correlation exists between the radio properties of these Z sources and their X-ray characteristics (see Section 4.2 for the results on GX 17+2). Tan et al. 1990 found that this relation does not hold for GX 5-1, where the large radio flares occurred when the source was near the bottom of the NB, while no such bright flares occurred when the source was on the horizontal branch. The origin of the correlation between the radio brightness and the X-ray spectral branches is unclear.

van der Laan models

As argued below, the van der Laan models (1966) seem appropriate for the description of most aspects of the radio spectra and variability of X-ray binaries. In these models it is assumed that a blob of material is ejected, which expands spherically. One assumes that the emission and absorption coefficients are appropriate to those of synchrotron emission from relativistic particles moving in what are, on average, random directions in randomly directed magnetic fields of average strength H. By assuming a power-law energy spectrum (of the relativistic particles) of the form \( N(E)dE \propto E^{-\gamma}dE \), where \( \gamma \) is a constant, one can show (see e.g. Ginzberg and Syrovatskii 1965) that synchrotron emission will produce a photon spectrum of the form:

\[
S_{\nu, r} = S_0(r/r_0)^3(\nu/\nu_0)^{5/2}[1 - e^{p(-\tau_{\nu, r})}]
\]  

(1.3.1)
Figure 1.3.2 A van der Laan model with free expansion, showing the flux density evolution at different frequencies, $5\nu_0$, $4\nu_0$, $3\nu_0$, $2\nu_0$ and $\nu_0$.

where

$$\tau_{\nu,r} = \tau_0 (r/r_0)^{-3-2\gamma} (\nu/\nu_0)^{-(\gamma+4)/2}$$  (1.3.2)

Here $\nu$ is the radio frequency, and $r$ the radius of a spherical emission region ($\tau_0$ and $r_0$ are normalization values). These equations show that the flux density of an optically thick cloud increases with time as $S \propto r^3$, whereas the flux density of an optically thin cloud decreases with time as $S \propto r^{-2\gamma}$. The optical depth decreases with time, and drops below unity at high frequencies first, and at low frequencies later. Thus the flux density at high frequencies reaches its maximum first, as illustrated in Fig. 1.3.2. In the free-expansion model the expansion velocity is constant, thus giving $r/r_0 = t/t_0$. The observed radio spectrum is often written as a power-law; $S_\nu \propto \nu^\alpha$. The synchrotron spectrum can be approximated by an optically thick part (with $\alpha = 2.5$) and an optically thin part (with $\alpha = 0.5 - 0.5\gamma$). If one plots the light curves at different radio frequencies, the maximum flux density is reached first at the higher frequencies, and then (at a lower peak flux density) at the lower frequencies. As the emission region ($r$) becomes larger, the peak in the flux density spectrum moves to lower frequencies. If one observes at a constant frequency band, the emission region is initially optically...
thick ($\alpha = 2.5$), increases in intensity, reaches a peak flux density, and then decays with an optically thin spectrum ($\alpha = 0.5 - 0.5\gamma$). The decay of the optically thin emission should follow the $r^{-2\gamma}$-law. In the case of free expansion, during the optically thin decaying phase $S_n \propto r^{0.5-0.5\gamma-2\gamma}$ (see Fig. 1.3.2). This is close to what is observed in the decay phase of radio outbursts of X-ray transients, (see Hjellming et al. 1988), with $\gamma$-values between 2 and 2.5.

A typical observed spectral index $\alpha$ of $-0.6$ in an optically thin synchrotron model gives $\gamma = 2.2$. For a decaying synchrotron model in a freely expanding cloud ($r \propto t$) this should give a relation of $S_n(t) \propto t^{-4.4}$. In the case of decelerated expansion the light curve should follow $t^{-2.2}$ for adiabatic expansion (energy conservation; $r \propto t^{1/2}$) and as $t^{-1.47}$ for expansion with momentum conservation ($r \propto t^{1/3}$), see Table 1.3.1.

One can also calculate what happens if a central source ejects identical energetic clouds at a constant rate that radiate according to the van der Laan models. In its simplest form the speed with which the clouds leave the X-ray binary system is larger than the expansion velocity of the clouds. Assuming that the clouds do not obscure each other, the total brightness is given by a simple addition of the contributions of separate clouds, and each develops according to its own brightness and spectral evolution. In this situation one will observe a constant radio flux and constant radio spectrum. The spectral index will depend on the $\gamma$-value and type of expansion of the individual clouds. The spectral indices expected for this second possibility are given in Table 1.3.1. One can see that the spectral indices are between those expected for the optically thick and thin cases.

A comparison between the van der Laan models and the observations

In the case of the persistent X-ray binaries, one observes persistent but variable radio emission. Since these sources show spectra which indicate that the emitting region is optically thin ($\alpha \sim -0.6$) at decreasing radio flux densities, and (in most cases) steeper spectra at increasing radio flux densities, one can consider the possibility that the total emission of these radio blobs is a simple addition of several blobs. Two extreme possibilities occur; one whereby all flux is dominated by the largest radio blob; and one whereby the flux originates from a very large number of (equal) blobs. The first case should give the optically thick rise ($\alpha = 2.5$) and optically thin decay ($\alpha$ depends on $\gamma$) of a radio flare. By increasing the number of blobs the spectral index during episodes of increasing radio flux densities may decrease from the above value of 2.5 to $-0.1$ (for an infinite number of blobs in the case of $\gamma$ is 2 and $p=1/3$, see Table 1.3.1). Similarly, during the decay the spectral index is expected to lie in the range $-1.0$ to 0.9.

If the radio emission originates from one or more of the above described expanding synchrotron clouds one expects it to have the following properties: (1) The variability will be largest at the highest frequencies. (2) The peak flux density should first be reached at the highest frequencies. (3) During a strongly rising radio flare, the spectral index will be between $-0.1$ and 2.5. (4) During a decaying radio flare, the spectral index will be between $-1.0$ and 1.0.

Some observed properties of X-ray binaries are in agreement with van der Laan models, in particular: (1) The spectra during the decay part of bright radio flares (in comparison with their average radio flux density) are well represented by a van der
\[ 2.50 \quad 0 \quad 0 \]
\[ -0.50 \quad 0 \quad 0 \]
\[ 0.78 \quad 5 \quad 5 \]
\[ 0.35 \quad 6 \quad 6 \]
\[ -0.06 \quad 8 \quad 8 \]

**Table 1.3.1** \( \alpha \) and \( \beta \) values for some simple van der Laan models

<table>
<thead>
<tr>
<th>model</th>
<th>( \alpha ) in ( S \propto \nu^\alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \gamma = 2 )</td>
</tr>
<tr>
<td>radio flare during optically thick rise</td>
<td>2.500</td>
</tr>
<tr>
<td>radio flare during optically thin decay</td>
<td>-0.500</td>
</tr>
<tr>
<td>persistent radio clouds ((p=1)^*)</td>
<td>0.785</td>
</tr>
<tr>
<td>persistent radio clouds ((p=1/2)^*)</td>
<td>0.356</td>
</tr>
<tr>
<td>persistent radio clouds ((p=1/3)^*)</td>
<td>-0.068</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>model</th>
<th>( \beta ) in ( S \propto t^\beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \gamma = 2 )</td>
</tr>
<tr>
<td>decay of optically thin flare ((p=1)^*)</td>
<td>-4.00</td>
</tr>
<tr>
<td>decay of optically thin flare ((p=1/2)^*)</td>
<td>-2.00</td>
</tr>
<tr>
<td>decay of optically thin flare ((p=1/3)^*)</td>
<td>-1.33</td>
</tr>
</tbody>
</table>

\* \( p \) indicates the type of expansion: \( r \propto t^p \);
\( p = 1 \) gives free expansion;
\( p = 1/2 \) gives adiabatic (energy conservation) expansion;
\( p = 1/3 \) gives slowed (momentum conservation) expansion.

Laan model. Their spectral index \( \alpha \) is \( \sim -0.6 \) (e.g. LS I +61°303, Cyg X-3, Sco X-1, GX 17+2), corresponding to a \( \gamma \) value of \( \sim 2.2 \). (2) The radio spectra of persistent radio sources are rather flat (Cyg X-1, Cyg X-3, Sco X-1). The spectral indices (between \( \sim -0.2 \) and 0.2) of these persistent radio sources suggest (in combination with \( \gamma = 2.2 \)) slowed expansion with \( p \sim 1/3 \) (see Table 1.3.1). (3) The maxima of the radio flux density at various frequencies seem to follow that of the van der Laan models, e.g. Cyg X-3 in Sept. 2–8 1972 (see Gregory et al. 1972). (4) During the radio flux density increase of LS I +61°303 and the above mentioned Cyg X-3 flare the spectra are rather steep, though not as steep as expected from one single radio emitting region.

Some aspects of the radio emission of X-ray binaries indicate that the van der Laan models may be too simple, or incomplete, to tell the full story. (1) In some cases the spectra of large radio flares are not given by optically thick spectra, but by optically thin spectra (\( \alpha \sim -0.6 \); large radio flares of Cyg X-3 in Sept. 20–30 1973; Sco X-1 on Sept. 29 1970). (2) Variability at lower frequencies has been reported to be larger than at higher frequencies (GX 13+1; Garcia et al. 1988). It is unclear whether incorrect mapping (Hjellming, private communication) of the area near GX 13+1 could be the origin of the larger variability at lower frequencies.

**Radio lobes near Z sources**

Two radio sources have been found at opposite sides (\( \sim 2' \)) from the Z source
1.4 Atoll sources

Sco X-1. It is likely, but not certain they are related to Sco X-1, see Section 4.3. Their radio flux densities are almost constant and have about the same average value as that of the central core. A search for similar radio lobes in the Z source GX 17+2 was performed in Section 4.3. No lobes were found.

1.4 Atoll sources

1.4.1 The energy spectral and power spectral behaviour of atoll sources

The atoll sources exhibit two branches in their X-ray colour-colour and X-ray colour-intensity diagrams, called 'banana' and 'island' (HK). Their fast-variability characteristics, very-low-frequency noise (VLFN) and high-frequency noise (HFN), are correlated with these spectral states (HK). Examples of the power spectra and colour-colour diagrams of two sources are shown in Fig. 1.4.1.

Strong HFN is present on the island states, while weaker, sometimes peaked HFN is present near the bottom of the banana branch. This component was earlier (in some cases) identified as QPO (see e.g. Section 3.1). The fractional rms variation of the HFN component is weakest near the upper part of the banana-branch. The fractional rms variation of the VLFN component increases from the island via the lower banana to the upper banana. This behaviour of the VLFN component is very similar to that of the VLFN component in Z sources, in that case going from the horizontal via the normal to the horizontal branch. The change in fractional rms variation of the HFN from the island to the banana state in atoll sources mimics that of the HBO from the horizontal via the normal to the flaring branch.

The energy spectra of the atoll sources in the island state look like power laws with index $\sim 2.0$ and a low-energy cutoff, probably due to absorption. The spectra in the banana branch show a strong high-energy cutoff.

Most atoll sources are regular X-ray burst sources. It is quite possible that all regular X-ray burst sources are atoll sources (by 'regular' I mean that they follow the general relations as found by van Paradijs, Penninx and Lewin (1988), thereby excluding the Z source GX 17+2, which has very different burst characteristics).

For some atoll sources the orbital period has been determined. In the case of 1820-30, which has an orbital period of $\sim 11$ minutes, the mass donor is probably a low-mass helium white dwarf. In the other three cases the orbital period is near 4 hours, suggesting (HK) that the mass donor is a low-mass main-sequence star. It has been suggested that the difference between Z sources and atoll sources is the result of a different evolutionary history, and that the mass donors of Z sources are giants, while most atoll sources are main-sequence stars.

The mass accretion rate

The X-ray luminosities of the atoll sources range between less than $\sim 0.5 \times 10^{-2}$ to $\sim 0.3 L_{\text{edd}}$.

The optical emission in 1735-44 (Corbet et al. 1989) is correlated with the position in the colour-colour diagram, with increasing optical emission from the island via the lower banana to the upper banana. 0748-67 (Motch et al. 1989), which is probably also
an atoll source, showed similar behaviour. This suggests that the island and banana states represent lower and higher accretion rates.

Details of the X-ray bursts (burst decay times [and correlated with this $\alpha$-values (see below)], burst spectra, variability of the waiting times) are correlated with the X-ray spectral state, but not with the X-ray flux (van der Klis et al. 1990). This correlation between burst properties is probably part of the same correlation that was found by van Paradijs et al. (1988) between burst properties and persistent X-ray luminosity over larger ranges of X-ray luminosity. Van der Klis et al. (1990) interpret this as a continuous increase of the mass accretion rate in the colour-colour diagram, from the island via the lower banana to the upper banana branch. This way one can have a general correlation between the X-ray flux and the mass accretion rate, and one can violate this correlation on a small scale (factor of two in X-ray flux).

1.4.2 Radiation at other wavelengths

*Optical/UV emission*

The optical/UV emission is dominated by emission resulting from X-ray heating of the accretion disk and of the hot side of the companion facing the X-ray source. Different viewing angles as a function of orbital phase can produce (for relatively large inclination angles) an orbital brightness variation. This can be used to determine the orbital periods.

An increase of X-ray flux ($\dot{M}$) will increase the optical flux (reprocessed X rays) and give rise to a correlation between optical and X-ray brightness.

The coincident X-ray/optical bursts observed so far show that the optical bursts are delayed ($\sim 1$ sec) and smoothed ($\sim 2$ sec) with respect to the X-ray bursts, consistent with the light travel time distance between neutron star and the reprocessing material (Pedersen et al. 1982). Most atoll sources have about the same $F_{\text{opt}}/F_x$ ($\sim 10^{-3}$) which gives for a disk temperature of $\sim 3 \times 10^4$ K an opening angle of $\sim 10^\circ$.

*Radio emission*

The atoll sources are very weak radio sources. Only one source has a clear, but weak (\(\leq 2\) mJy), variable radio counter part, GX 13+1. Two very weak (\(\leq 0.7\) mJy) radio sources have been detected in globular clusters, which also contain X-ray burst sources and could be atoll sources (see Machin et al. 1990). The remaining atoll sources have upper limits to their radio flux density of $\sim 0.3$ mJy at 5 GHz (e.g. Grindlay and Seaquist 1986). It is likely that all atoll sources are weak radio sources.

1.4.3 X-ray bursts

When the mass accretion rate onto the neutron star is very large (\(\geq 0.3 L_{\text{edd}}\)) continuous nuclear fusion takes place on the neutron star surface (e.g. GX 9+1, GX 9+9 and 1820-30 and GX 3+1 in their bright state). When the mass accretion rate is somewhat lower ($10^{-3} - 0.3 L_{\text{edd}}$) continuous burning can not be maintained. When the newly accreted matter has built up sufficient pressure, it is ignited and thermonuclear fusion takes place
1.4 Atoll sources

Figure 1.4.1 The X-ray colour-colour diagrams (top) and power spectra (bottom) of the atoll sources GX 9+1 and 1735-44 (figures taken from HK)

in a runaway process and an X-ray burst is observed. When the mass accretion rate decreases further the burst rate decreases, and the waiting times between bursts may become extremely long. For reviews on X-ray bursts, see Lewin and Joss (1983) and Damen (1990).

Burst properties

Prior to the launch of EXOSAT, observations of X-ray burst sources were hampered by the fact that X-ray observatories always orbited the Earth in low orbits, so that ob-
Observations of a single source were interrupted every ~ 90 min due to Earth occultations. This problem could be avoided with EXOSAT, which had an orbital period of ~ 90 hr. The main characteristics of X-ray bursts have been summarized by Damen (1990). We will briefly describe the observational results that are available from burst analysis.

- There is a wide range of waiting times between bursts from a single source. They can be as short as 4 min, and as long as at least ~ 35 hours (see Section 2.3). Sources sometimes show active burst periods alternating with inactive periods; sometimes the waiting times are very regular (island state) while at other times the waiting times are very irregular. In some sources the burst interval seems to be related to the level of the persistent flux. For a typical bursting behaviour of a normal burst source (1636-53), see Section 2.1. Notice that the burst energy is roughly proportional to the amount of accreted material (waiting time), as expected.

- The typical total energy released during a burst is $\gtrsim 10^{39}$ erg. The burst energy is (in the thermonuclear flash model) determined by the available amount of fusion material, which is determined by the mass accretion rate and the waiting time since the previous burst.

- The typical burst peak luminosities are $\sim 10^{37-38}$ erg s$^{-1}$. The burst peak luminosities correlate with waiting times. A burst peak is limited to the Eddington limit ($L_{\text{edd}} = 2.5/(1+X) \times 10^{38}$ M$\odot$ erg s$^{-1}$, $X$ being the hydrogen mass abundance). When this limit is reached, photospheric radius expansion is observed. In most cases the flux reaches the Eddington limit in $\lesssim 1$ sec and the photospheric radius expands, in some cases to $\gtrsim 200$ km. During the subsequent seconds the photosphere contracts fairly slowly (in comparison with the photospheric expansion). During this process the luminosity remains at the Eddington limit, and, as the size of the emitting region decreases, the temperature increases. After the photosphere reaches the surface of the neutron star ($R=R_{\text{ns}}$), the temperature and flux decrease. During the expansion phase the temperature can be extremely low ($< 1$ keV), in which case most of the photons are emitted outside the X-ray band. In that case the flux will show a minimum (or even go to zero) during this phase; the profile is double-peaked.

- The rise times of the radius expansion bursts are short, $\leq 1$ sec. The rise times of the bursts which do not reach the Eddington limit are longer, up to $\sim 10$ s. A clear correlation of the rise times with other properties is not present, although there is a suggestion that the rise times are longer in the island state than in the banana state (see Damen 1990).

- The decay times vary from seconds to minutes, see e.g. Section 2.4.

- The ratio of the integrated persistent flux before a burst and the integrated burst flux (burst fluence), $\alpha$, is in general on the order of $\sim 100$, as is expected from the ratio of gravitational energy to a neutron star and thermonuclear fusion of H and He to heavier elements. Large deviations from this value have been observed in several sources (Section 2.4).
1.4 Atoll sources

- **Burst spectra.** Time resolved spectral analyses of X-ray bursts have shown that the X-ray burst spectra are well fitted by Planck curves. As the X-ray brightness decays during a burst, the emitting area remains constant, which gives a decreasing temperature during burst decay. The blackbody fits give temperature and flux, thus providing a solid angle as a function of time. If one knew the distance to a source one would be able to determine (in principle) the radius of the neutron star. A basic uncertainty in this type of radius determination is the effect of the radiation transfer through the neutron star atmosphere on the spectrum. Detailed theoretical models (e.g. London, Taam and Howard 1984) can be used to take this effect into account to determine neutron star radii. The correction is generally expressed in terms of the ratio $T_{\text{col}}/T_{\text{eff}}$, where $T_{\text{col}}$ is the observed colour temperature in the X-ray spectrum and $T_{\text{eff}}$ is the effective temperature. According to these theoretical models the $T_{\text{col}}/T_{\text{eff}}$ values are $\sim 1.4$. However, the observed relation between the $T_{\text{col}}/T_{\text{eff}}$ appears to be inconsistent with the theoretical models (see Section 2.5), and the derived radii contain much larger errors than previously claimed. Van der Klis et al. (1990), following up on work of Damen et al. (1989), showed that the $T_{\text{col}}/T_{\text{eff}}$ values strongly depend on other parameters, in particular on the position in the colour-colour diagram. This suggests that the atmosphere of the neutron star is different between the ‘banana’ and the ‘island’ state. Parameters that are derived from this type of burst analysis might, if progress is made on the theoretical side, give insight on the atmospheres, masses and radii of the neutron stars.

The thermonuclear flash model for type 1 bursts is now generally accepted as being correct. This model can explain most of the observed global properties of bursts. However, a number of unresolved problems remain, in particular relating to the recurrence behaviour of bursts, and the relation between bursts and persistent properties. It has been suggested that the interaction of thermonuclear flashes with the neutron star core, and the influence of bursts themselves on the detailed structure of the outer layers of the neutron star, are causing the apparent irregularity of the bursts recurrence.

**References**


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Introduction


