A study of x-ray bursts with EXOSAT
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Chapter 1

Introduction and summary

1.1 Preface

This Thesis deals with the spectral and long-term temporal behaviour of X-ray burst sources. The study of this behaviour can provide information on the geometrical structure of these systems and the internal structure of neutron stars. This Chapter starts with a brief historical overview of X-ray astronomy, followed by a description of the objects studied in this Thesis. In the remainder of this Chapter I describe the current state of our knowledge on X-ray burst sources and point at some remaining problems. The Chapter is finished with a short summary of the contents of this Thesis and the most important results of my studies. Since the remainder of this Thesis, with the exception of Chapter 2, has been (or will be) published as papers in various journals, some overlap between this Chapter and the introductory sections of the following Chapters has been inevitable.

1.2 X-ray astronomy in the pre-EXOSAT era

X-ray astronomy is a relatively young branch of astronomy. Since X rays are effectively absorbed by the Earth atmosphere, observations of X rays from space have only become possible with the advent of rockets and balloons to carry instruments to large altitudes. In 1948 the first celestial X rays were observed from the Sun. In the years following, the X-ray emission of the Sun was extensively studied. Several attempts 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. Thus, the discovery of the first extra-solar X-ray source (Sco X-1) in June 1962 was more or less accidental, during a rocket flight aimed at observing the Moon and testing new, sensitive instruments (Giacconi et al. 1962). The existence of sources emitting most of their energy in X rays was unexpected; this emission could not be of normal stellar origin. In the years following, about 30 bright galactic X-ray sources were discovered during rocket experiments. With the first X-ray observing satellite, UHURU, launched in 1970, more than 300 sources were discovered. In the 1970's, UHURU was followed by many other X-ray observing satellites (Vela-5, Copernicus, Ariel V, ANS, SAS 3, 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.

1.2.1 X-ray binaries

In 1966 a rocket flight with instruments having a high angular resolution established the star-like dimensions of Sco X-1 (Gursky et al. 1966a), and provided a position accurate enough (Gursky et al. 1966b) to enable the identification of the optical counterpart 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 in two groups, the high-mass and the low-mass X-ray binaries, with the following properties:

1. **High-mass X-ray Binaries**

   These objects consist of a compact object (neutron star or black hole) and a massive (\( > 10 \, M_\odot \)) early-type companion star. The optical emission is dominated by the massive star (typically \( L_x/L_{\text{opt}} \gtrsim 1 \)). The UV spectrum shows clear evidence for the presence of a stellar wind from the massive companion, which is probably the source of the mass transfer to the compact object. In some cases there is evidence that an accretion disk is formed around the compact object. Almost all of the high-mass X-ray binaries show regular pulsations in their X-ray luminosity. This pulsation is caused by the strong magnetic field (\( \sim 10^{12} \, \text{G} \)) 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 fact that the companion is an early-type massive star, indicates that the high-mass X-ray binaries are relatively young. This is consistent with the fact that these objects are concentrated towards the galactic plane where regions of recent star formation are located.

2. **Low-mass X-ray binaries**

   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 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 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 weak ($\sim 10^9$ G).

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

1.2.2 X-ray burst sources

X-ray bursts were discovered in 1975 independently by Grindlay et al. (1976) using the ANS satellite and by Belian, Conner and Evans (1976) using Vela-5. The bursts observed by Grindlay et al. originated in the globular cluster NGC 6624. Within a year, more than 20 burst sources were found, both in globular clusters and in the galactic bulge (for a review see Lewin and Joss 1983).

Several models were proposed to explain these bursts; they can be divided broadly into two classes: (i) models incorporating some kind of instability in the accretion flow (Svestka 1976; Henriksen 1976; Joss and Rappaport 1977; Baan 1977; Lamb et al. 1977; Wheeler 1977; Liang 1977); and (ii) models assuming thermonuclear flashes in the freshly accreted layers on the surface of the neutron star (Woosley and Taam 1976; Maraschi and Cavaliere 1977). The latter type of models had the disadvantage that they could not explain the observations of the so-called Rapid Burster (Lewin et al. 1976). This transient source showed bursts in very rapid succession on time scales of seconds to minutes. The thermonuclear flash model is not able to explain how enough nuclear fuel can accrete on the surface of the neutron star in the short interval between these bursts. This problem was solved with the discovery that the Rapid Burster shows two different kinds of bursts (Hoffman, Marshall and Lewin 1977, 1978). The rapid bursts belong to the so-called Type II class; they show no spectral softening during burst decay and are caused by accretion instabilities. The other type of bursts (Type I) is similar to the bursts observed in other sources; they show spectral softening during decay and are caused by thermonuclear flashes. Until now, the Rapid Burster is the only known burst source emitting both types of bursts.

The spectral softening in the decay of the Type I bursts was discovered by Swank et al. (1977). They found that the spectral evolution of a very long burst from 4U 1724-30 was consistent with the cooling of a blackbody surface. Hoffman, Lewin and Doty (1977a, 1977b) showed for two sources that the blackbody radius during decay is $\sim 10$ km, assuming a source distance of 10 kpc. This was the first strong indication that the collapsed object in these systems is a neutron star. Indications that the burst sources belong to the class of the low-mass X-ray binaries came from the first optical identification of a burst source, 4U 1735-44, by McClintock, Canizares and Backman (1978); burst sources have a faint blue optical counterpart, similar to that of Sco X-1 (see e.g. Van Paradijs (1983) for a review of the optical properties of low-mass X-ray binaries). The ratio of X ray to optical luminosity is $\gtrsim 10^2$. The first evidence for an orbital period of an X-ray burst source was found by Pedersen, Van Paradijs and Lewin (1981) in the optical emission of 4U/MXB 1636-53. Since 1980, orbital periods have been found for $\sim 25$ low-mass X-ray binaries; they are in the range between $\sim 11$ min and $\sim 10$ days.
1.3. Properties of X-ray burst sources

1.3.1 General properties

In Fig. 1.1 the sky distribution of the presently known X-ray burst sources is shown (the sources and their galactic coordinates are listed in Table 1.1). From this map it is clear that burst sources are concentrated towards the galactic center.

The optical emission of X-ray bursters is dominated by emission resulting from X-ray heating of the accretion disk. The optical spectrum shows no normal stellar absorption lines, but weak emission features are present. There is evidence (see e.g. Canizares, McClintock and Grindlay 1979) for Doppler velocities of $\sim 10^3$ km/s, indicating fast moving gas streams and the presence of a disk. In a number of cases optical bursts have been observed coincident with X-ray bursts (e.g. Pedersen et al. 1982).

For most burst sources the companion is a late-type star on or near the Main Sequence, with a mass below $\sim 1.0$ $M_\odot$. This follows from the distribution of known orbital periods, and from the late-type (K) spectral characteristics of the optical counterparts of some transient burst sources during quiescence, when the optical emission from the disk has become very weak. In the globular-cluster source 4U 1820-30, the observed orbital period of $\sim 11$ min, observed in X rays, suggests that the companion is most likely a white dwarf.

Figure 1.1 The sky distribution of presently known X-ray burst sources (see Table 1.1). This plot is in galactic coordinates. Some well-known sources have been indicated.
Table 1.1 Presently known X-ray burst sources

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<td>-1.5</td>
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</table>

1 If the burst source is a member of a Globular Cluster, the name of the cluster is given in this column.
2 There are probably at least four distinct Galactic Center sources. The spatial resolution of non-imaging X-ray detectors is not good enough to accurately determine their positions.
1.3. Properties of X-ray burst sources

Most of the burst sources show persistent X-ray emission between bursts. In a few cases the persistent source is too weak to be detected with current instruments. The persistent X-ray spectrum is usually ‘soft’ (\(kT \sim 5\) keV).

It is important to note that none of the bursting sources show periodic X-ray pulsations. Apparently, bursts and pulsations are mutually exclusive phenomena.

These properties show clearly that the burst source are a subgroup of the low-mass X-ray binaries (see Section 1.2.1).

1.3.2 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 observations of a single source were interrupted every \(\sim 1\) hr due to Earth occultations. This problem was circumvented with EXOSAT, which had an orbital period of \(\sim 90\) hr (see Chapter 2 for details).

The main characteristics of X-ray bursts as known prior to the launch of EXOSAT can be summarized as follows (see Lewin and Joss 1983 for a review; for a summary of the most important discoveries by EXOSAT, I refer to the introductory sections of Chapters 3–7 of this Thesis):

- There is a wide range of waiting times between bursts from a single source. They can be as short as 4 min, and probably as long as at least a day. Some sources show active burst periods alternated by inactive periods, other sources show bursts at very regular intervals. In some sources the burst interval seems to be related with the level of the persistent flux.

- Typical burst peak luminosities are \(\geq 10^{38}\) erg s\(^{-1}\), and the total energy released during a burst is \(\geq 10^{39}\) erg (assuming a distance of 10 kpc). Peak fluxes of bursts from a single source may vary up to a factor of \(\sim 10\). A gross positive correlation is present between the peak flux and the total energy content of bursts (see e.g. Basinska et al. 1984; Sztajno et al. 1983). There is evidence for photospheric radius expansion during very intense bursts (Hoffman, Cominsky and Lewin 1980; Grindlay et al. 1980; Tawara et al. 1984; Lewin, Vacca and Basinska 1984), which suggests that the Eddington limit is reached at the peak of these bursts.

- There is a correlation between the total energy in a burst and its waiting time since the previous burst (see e.g. Hoffman, Lewin and Doty 1977; Basinska et al. 1984).

- Burst profiles come in a large variety. Rise times range from \(\sim 1\) s to \(\sim 10\) s and decay times from seconds to minutes. The decay times are much shorter at high energies than at low energies (see Section 1.3.4). Double-peaked bursts have been reported. In some sources, changes in burst profile are related to changes in the level of the persistent emission. In 4U 1820-30 the decay time of the burst shortened as the persistent emission increased (Clark et al. 1977). In 4U 1608-52 ‘fast’ bursts (i.e. fast rise and fast decay) were observed at high
persistent flux levels, while ‘slow’ bursts were observed at lower persistent flux levels (Murakami et al. 1980).

- The ratio, \( \alpha \), of integrated persistent flux since the previous burst and integrated burst flux, varies from \( \sim 25 \) to \( \geq 100 \). The few bursts with very short waiting times have \( \alpha \)-values \( \leq 10 \).

### 1.3.3 Burst models

The thermonuclear flash model for Type I bursts is now generally accepted as being correct. This model can explain most of the observed global properties of bursts, e.g. the typical burst energies and peak fluxes, the observed relation between burst peak flux and the burst fluence with the waiting time since the previous burst, the observed burst durations and rise and decay times. 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.

For a detailed description of the thermonuclear flash model and the most important remaining problems, I refer to Chapter 3 of this Thesis.

### 1.3.4 Burst spectra

As mentioned before, Swank et al. (1977) were the first to discover that burst spectra from type I bursts can at each time during the burst be well fitted by a blackbody spectrum. However, it was soon realized that a detailed model of the emission spectrum during bursts is necessary in order to draw any conclusions regarding source properties from the observed spectrum. At the temperatures and densities prevailing in the neutron star atmosphere, a large fraction of the opacity is due to scattering. Already in 1969, Zel’dovich and Shakura (1969) incorporated Thomson scattering in model calculations of spectra emerging from a isothermal neutron star atmosphere. They concluded that the shape of the emerging spectrum differs considerably from that of a blackbody (‘Modified Black Body’). Van Paradijs (1982) and Czerny and Sztajno (1983) calculated simplified models assuming atmospheres in hydrostatic equilibrium, a temperature which increases with optical depth, and including Thomson scattering, free-free and bound-free absorption as sources of opacity. They found that the burst spectrum emerging from the neutron star atmosphere is most likely harder than a Planckian spectrum with a similar effective temperature, due to scattering processes in the atmosphere.

London, Taam and Howard (1984, 1986, hereafter LTH) were the first to construct self-consistent model atmospheres in radiative and hydrostatic equilibrium. This means that their models are not appropriate for luminosities at or above the Eddington limit, because this will result in a radiation-driven outflowing atmosphere which is not in hydrostatic equilibrium. In these models, energy transport occurs only by means of radiation, which means that convection is not considered. This simplification is most likely correct since model calculations of the thermonuclear flash on
1.3. Properties of X-ray burst sources

![Graph showing the resulting spectrum of one of the models of London, Howard and Taam (1984).](image)

**Figure 1.2** Resulting spectrum of one of the models of London, Howard and Taam (1984). The model parameters are $kT_{\text{eff}} = 1.08$ keV, $g = 10^{14}$ cm s$^{-2}$, and solar abundances. The solid histogram shows the calculated spectrum. The dash-dot curve is the Planck function at $T_{\text{eff}}$. The solid curve is the Planck function which best fits the calculated spectrum. The short dashed histogram is a spectrum calculated without Comptonization. Figure taken from London, Taam and Howard (1984).

the surface of the neutron star show that convection zones do not extend as far as the atmosphere (see also Chapter 3 of this Thesis). In addition LTH made the following simplifying assumptions:

- Chemical composition inhomogeneities are neglected.
  This is justified because the timescales for elemental diffusion through the atmosphere are much longer than the time scale at which matter is accreted onto the neutron star surface (Fontaine and Michaud 1979).

- The influence of magnetic fields is neglected.
  The effect of the magnetic field on the pressure balance in the atmosphere becomes important at a field strength greater than $\sim 10^8$ G. At present, the question of the magnitude of the magnetic field in burst sources is not settled. Based on the absence of pulsations in the X-ray emission and on the absence of cyclotron lines in the spectrum, an upper limit on the field strength of $\sim 10^9$ G is often assumed (e.g. Alpar and Shaham 1985).

- The influence of the ongoing accretion during a burst is neglected.
This is justified by the fact that the ram pressure of the infalling matter is smaller than the atmospheric pressure.

In their calculations LTH include in the opacity free-free processes due to ionized H and He, bound-free K-shell transitions from Fe$^{+24}$ and Fe$^{+25}$ and Compton scattering in the Kompane’ets approximation (Kompane’ets 1957; see also Rybicki and Lightman 1979). LTH calculated model atmospheres for various combinations of effective temperature, surface gravity and chemical abundance. The results of these numerical calculations show that Comptonization modifies the spectrum considerably. In Fig. 1.2 an example of a resulting spectrum is shown (solid histogram), together with the Planck function at the same effective temperature (dashed-dotted curve) and a model spectrum calculated without Comptonization (dashed histogram). From this example it is clear that at relatively low effective temperatures ($kT_{\text{eff}} = 1 \text{ keV}$) Comptonization has little effect at low photon energies, but reduces the flux considerably at energies $\gtrsim 15 \text{ keV}$. At higher effective temperatures the influence of Comptonization is stronger and shifts the resulting spectrum considerably to lower energies compared to a spectrum calculated without Comptonization. In all models, the resulting spectrum is shifted to higher energies compared to the Planck function with the same $T_{\text{eff}}$. This shift can be quantified by fitting a Planck function to the calculated spectrum. LTH find that such a fit generally gives good results. In Table 1.2 the ‘spectral hardening factors’, defined as the ratio of the fitted colour temperature, $T_c$, and the effective temperature, $T_{\text{eff}}$, are given.

Several authors calculated neutron star model atmospheres using essentially the same method as LTH. Ebisuzaki and Nomoto (1986) and Ebisuzaki (1987) calculated models for Helium-rich atmospheres near the Eddington limit. Lapidus, Synyaev and Titarchuk (1986) and Babul and Paczyński (1987) extended the calculations to atmospheres rich in heavy elements. Besides the hydrostatic-equilibrium models, Foster, Ross and Fabian (1986) also calculated models with constant density throughout the atmosphere. Titarchuk (1988) derived analytical expressions for burst spectra, including the effect of Comptonization in de Kompane’ets approximation. Madej (1989) used a more general description of the Comptonization process than the Kompane’ets approximation, including also scattering events with a large energy exchange between photon and electron.

All of the above mentioned studies have in common that they find a hardening of the spectrum compared to a Planckian spectrum of the same effective temperature. Spectral hardening factors, $T_c/T_{\text{eff}}$, are typically about 1.7. However, in using these factors to correct the fitted colour temperature of ‘real’ spectra, the influence of the detector response of the observing instrument must be taken into account.

The results of the model calculations have an important consequence for the interpretation of observed burst spectra. As described in the next Chapters of this Thesis, observed burst spectra can in general be described very well by a Planck function. The model calculations of LTH, however, show that it is not allowed to identify the fitted (colour) temperature directly with the effective temperature of the neutron star atmosphere. Knowledge of the relation between $T_c$ and $T_{\text{eff}}$ is essential in order to derive trustworthy results on e.g. the mass-radius relation of the neutron star from burst observations (see Chapters 5 and 7 of this Thesis).
1.3. Properties of X-ray burst sources

Table 1.2 Parameters of numerical models by London, Taam and Howard (1986)

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$^1k T_{\text{eff}}$ is the effective temperature (in keV), $g$ the gravity (in cm s$^{-2}$) and $Fe$ the iron abundance (relative to solar, which is taken to be $3.4 \times 10^{-5}$ by number relative to Hydrogen). $T_c$ is the spectral temperature found by fitting a normalized Planck function to the calculated output spectrum.

$^2$Model 16 was constructed without Comptonization, that is assuming purely elastic electron scattering.

$^3$Model 17 has a pure Helium composition.

1.3.5 The mass-radius relation of the neutron star

The very high densities present in the neutron star's interior (central density in excess of the nuclear density, i.e. $\rho_c > 2.8 \times 10^{14}$ g cm$^{-3}$) are at present very hard to study in a laboratory environment. Therefore, the study of neutron stars may be the only way to gain insight in the structure of matter at supra-nuclear densities. The details of the equation of state of the neutron star matter depend on the interaction between nucleons, and have a direct consequence for observable properties of the neutron star, such as its mass and radius. This is illustrated in Fig. 1.3, which shows theoretical mass-radius relations for neutron stars, based on several assumed equations of state. One distinguishes 'soft' and 'hard' equations of state, the 'soft' ones resulting in smaller radii at a given mass.

Van Paradijs (1979) showed that, in principle, the observed blackbody radii in X-ray bursts, combined with general-relativistic effects, can put constraints on the mass and radius of the neutron star. The relation between the blackbody radius, as
The mass-radius relation of neutron stars for a variety of equations of state, proposed by Pandharipande and Smith (1975a; PS1), Pandharipande and Smith (1975b; PS2), Bethe and Johnson (1974; BJ), Pandharipande (1971; P), Maxwell and Weise (1976; MW), and generalized by Baym and Pethick (1979).

Figure 1.3 The mass-radius relation of neutron stars for a variety of equations of state, proposed by Pandharipande and Smith (1975a; PS1), Pandharipande and Smith (1975b; PS2), Bethe and Johnson (1974; BJ), Pandharipande (1971; P), Maxwell and Weise (1976; MW). Figure taken from Baym and Pethick (1979).

measured by an observer at infinity, $R_\infty$, and the real radius, $R_*$, is given by:

$$R_\infty = R_*(1 + z_*) = R_*(1 - \frac{R_*}{R_s})^{-1/2} \quad (1.1)$$

Here $z_*$ is the gravitational redshift at the neutron star surface and $R_s = 2GM/c^2$ is the Schwarzschild radius of the neutron star. From this relation one can infer that a minimum value of the observed radius is reached at $R_* = 1.5R_s$. At $R_* < 1.5R_s$ only photons emitted within a certain angle from the radial direction can escape to infinity. This effect will effectively reduce the observed flux from the source and therefore reduce the inferred radius $R_\infty$. For isotropic emission from the neutron star surface one can show that $R_\infty$ will be constant for $R_* \leq 1.5R_s$:

$$R_\infty = \frac{3}{2}\sqrt{3}R_s \quad \text{for} \quad R_* \leq 1.5R_s \quad (1.2)$$

In turn, an observed value for $R_\infty$, immediately leads to an upper limit on the mass of the neutron star:

$$M = \frac{c^2R_\infty}{3G\sqrt{3}} = \frac{R_\infty [\text{km}]}{7.70} M_\odot \quad (1.3)$$

These results are shown graphically in Fig. 1.4, which contains curves of allowed masses and radii assuming several different values of $R_\infty$. 
1.3. Properties of X-ray burst sources

Figure 1.4 Mass-radius relation of a neutron star for a number of observed values of the blackbody radius. Each curve is labeled with a value for the observed blackbody radius at infinity \( R_\infty \) (5, 10 and 15 km). The straight lines show the relation between mass and radius for neutron stars having different gravitational redshifts \( z \). See text for more details.

From Fig. 1.4 it is clear that there are essentially three mutually related, unknown parameters involved: \( M \), \( R_\ast \), and \( z \). For given value \( R_\infty \), at least one of these parameters must be known to derive values for the other two.

A measurement of the gravitational redshift may be derived if a discrete, identifiable feature is present in the spectrum. Recently, absorption lines at 4.1 ± 0.1 keV have been reported in burst spectra from 1636-53 (Waki et al. 1984), 1608-52 (Nakamura et al. 1988), and 1747-214 (Magnier et al. 1989). Assuming that this line is due to Fe\(^{+24}\), Waki et al. (1984) derived \( 1 + z \sim 1.6 \). For a discussion on these results I refer to Chapter 7 of this Thesis.

Another method to determine the gravitational redshift is based on the fact that during radius expansion the luminosity of the source remains within a few percent of the Eddington luminosity. However, due to the expansion the gravitational redshift changes, resulting in a variation in the observed luminosity at infinity. This variation can be used to determine the gravitational redshift at the neutron star surface, using observations of very strong bursts showing photospheric radius expansion. This method is discussed and applied to several burst sources in Chapter 7 of this Thesis.

A third method to derive constraints on the mass and radius of the neutron star from burst observations has been used by several authors (e.g. Fujimoto and Taam 1986; and Sztajno et al. 1987). This method combines observations during radius
expansion with those made in the tail of the burst. In the tail of the burst we have:

\[ 4\pi d^2 \xi F_{b,\infty} = 4\pi R_{\infty}^2 \sigma T_{b,\infty}^4 \tag{1.4} \]

Here, \( d \) is the distance to the source; \( F_{b,\infty} \) is the measured burst flux at infinity; \( T_{b,\infty} \) is the blackbody temperature at infinity; and \( \xi \) is an anisotropy factor. Assuming that during radius expansion \( R > R_* \), one can then neglect the redshift, and:

\[ L_{Edd}(R > R_*) \approx 4\pi cGM/\kappa = 4\pi d^2 \xi F_{Edd,\infty}(R > R_*) \tag{1.5} \]

Here \( \kappa \) is the electron scattering opacity during radius expansion.

Dividing these two equations gives (using eq. 1.1):

\[ \frac{F_{b,\infty}}{F_{Edd,\infty} T_{b,\infty}^4} = R_*^2 \left( 1 - \frac{R_*}{R_0} \right)^{-1} \frac{\sigma}{cGM} \kappa \tag{1.6} \]

The left side of this equation consists of observable quantities. Given a certain value for \( \kappa \), one can determine a relation between the mass and the radius of the neutron star. An additional determination of one of the parameters \( M, R \) or \( z_* \) is needed to further constrain the mass and radius of the neutron star.

In the above it has been assumed that in the tail of the burst the effective temperature equals the blackbody temperature as obtained from the shape of the burst spectrum. As pointed out in the previous section, model atmosphere calculations show that this is not a good assumption. Therefore, one needs to know the exact relation between colour temperature and effective temperature.

### 1.4 Summary of this Thesis

This Thesis contains a study of X-ray burst sources using data collected with the EXOSAT Medium Energy (ME) instrument. In Chapter 2, I give a description of this instrument and of the methods used in the basic analysis of its data. In the Chapters following, three main topics have been addressed: (i) the properties of X-ray bursts; (ii) the detailed shape of the burst spectrum; (iii) the determination of the mass-radius relation of neutron stars by means of burst observations.

Chapter 3 gives an extensive overview of the properties of the X-ray bursts from one particular source, 4U/MXB 1636-53. An interesting result from this study is that the bursts from this source show variations in total energy and duration which seem to be related with variations in the spectral and temporal properties of the persistent emission of the source.

Chapter 4 is devoted to the study of bursts from 4U 1608-52. From this source only two bursts have been observed with EXOSAT, which are both very strong but show no indication for expansion of the photosphere. One of these bursts shows a dip in its bolometric flux profile shortly after maximum flux has been reached. Possible explanations for this dip could be the multiple release of energy during the burst or the existence of a (possibly burst induced) hot plasma cloud along the line of sight which absorbs and scatters the burst emission. The spectra from these bursts show large deviations from a Planck function, which can not be explained with current model atmospheres.
In Chapter 5 we show that the inferred blackbody radius in the tail of the bursts from 1636-53 and EXO 0748-676 varies considerably from burst to burst and that this variation is correlated with variations in the duration of the bursts. These variations in radius are so large that they seem inexplicable with current models for burst spectra (e.g. the models of London, Taam and Howard 1986; see Section 1.3.4).

In Chapter 6 we study the detailed shape of the burst spectra from 1636-53 in conjunction with the shape of spectra of the persistent emission of this source. From this comparison we arrive at the conclusion that the inner accretion flow towards the neutron star in this system is most likely geometrically thin.

In Chapter 7 we try to determine the gravitational redshift from the surface of the neutron star in four different sources, using observations of strong bursts which show radius expansion. We show that detailed models for burst spectra during radius expansion, combined with more sensitive X-ray observing instruments, are needed to put significant constraints on this redshift.

References

Friedman, H.: 1959, *Proc. IRE* 47, 278
References


