A study of x-ray bursts with EXOSAT

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Chapter 7

X-ray bursts with photospheric radius expansion and the gravitational redshift of neutron stars

A shorter version of this Chapter has been submitted to Astron. Astrophys.

Summary

Very strong X-ray bursts show photospheric radius expansion during which the burst luminosity is expected to remain constant at the Eddington limit. The Eddington luminosity as measured by a distant observer depends on the gravitational redshift factor and therefore on the radius of the photosphere. We describe a method which allows, in principle, to determine the gravitational redshift from the surface of a neutron star from observations of bursts with radius expansion. We report here in detail the results we obtained from an application of this method to four burst sources. We find that the method is very sensitive to systematic errors, particularly due to possible variations during the photospheric expansion of (i) the photospheric composition, (ii) the persistent X-ray emission, and (iii) the shape of the burst spectrum. As a consequence the measured values of the gravitational redshift are too uncertain to put significant constraints on neutron star properties. However, future theoretical studies of neutron star winds during the phase of radius expansion and of accretion onto weakly magnetized neutron stars may change this.

Key words: X-ray bursts - neutron stars

7.1 Introduction

Several observational methods are available which, in principle, can lead to a constraint on the mass-radius relation of neutron stars, and thereby to information on the equation of state of matter at supra-nuclear density.

Very accurate masses have been obtained from orbital analyses of pulse arrival times for the binary radio pulsars PSR 1916+13 (Taylor and Weisberg 1982) and PSR
0021-72A (Ables et al. 1989), whose orbital properties contain measurable general-relativistic effects. In addition, pulse-arrival times of massive binary X-ray pulsars, in combination with radial-velocity observations of their massive companions, provide neutron star masses. The results obtained so far (Joss and Rappaport 1984; Pietsch et al. 1984) are consistent with a 'canonical' neutron star mass close to 1.4 $M_\odot$; however, mass differences of more than 0.5 $M_\odot$ cannot at present be excluded. These results are consistent with most equations of state proposed so far, except for extremely 'soft' ones (i.e. very compressible neutron star matter; cf. Arnett and Bowers 1977; Baym and Pethick 1979).

Time-resolved X-ray burst spectra may provide information on neutron star radii. This method is based on the assumption that during X-ray bursts which are the result of thermonuclear flashes on the surface of an accreting weakly magnetized neutron star in a low-mass X-ray binary (see, e.g., Lewin and Joss 1983), the whole surface of the neutron star is emitting X rays. In the simplest version of this method it is assumed that the burst emission is independent of the persistent X-ray emission (due to accretion) and that its spectral energy distribution is a Planck function (Swank et al. 1977; Hoffman, Lewin and Doty 1977; Van Paradijs 1978). For a distant observer¹ the combined (bolometric) flux, $F_\infty$, and the (blackbody) temperature, $T_\infty$, provide an estimate of the blackbody radius $R_\infty$ of the neutron star through the expression

$$\frac{R_\infty}{d} = \sqrt{\frac{\xi F_\infty}{\sigma T_\infty^4}}$$

(7.1)

Here $d$ is the source distance which for most X-ray burst sources is unknown (there are only a few exceptions; see e.g. Van Paradijs 1983; Vacca, Lewin and Van Paradijs 1986), and $\xi$ is an anisotropy factor (see Sztajno et al. 1987).

Since the radius of a neutron star is not much larger than its Schwarzschild radius, general-relativistic effects cannot be ignored and one can show (Van Paradijs 1979; Goldman 1979) that a particular value of the blackbody radius $R_\infty$, as measured by a distant observer (see eq. 1), implies a relation between the mass, $M$, and radius, $R_*$, of the neutron star, according to the expression:

$$R_\infty = R_*(1 + z_*) = \frac{R_*}{\sqrt{1 - \frac{2GM}{R_* c^2}}}$$

(7.2)

(Eq. 2 is strictly valid only for non-rotating neutron stars; for rotation periods in excess of a few ms this approximation is still very good. Note that to measure $R_\infty$ a value for the distance is required).

For bursts with radius expansion a second relation between mass, radius and distance can be derived from the fact that then the luminosity equals the Eddington limit (see below). This method has been applied by Fujimoto and Taam (1986) and Sztajno et al. (1987) to derive mass-radius relations which are independent of the source distance.

¹In this paper we will indicate the quantities radius ($R$), temperature ($T$), flux ($F$), and luminosity ($L$), as measured by an observer at very large distance from the neutron star with subscript $\infty$; without a subscript these symbols indicate values measured by a local observer (i.e. near the neutron star); values measured by an observer on the surface of the neutron star have subscript $*$. 
The assumption that the spectrum during an X-ray burst is that of a blackbody is not correct (Van Paradijs 1982; Czerny and Sztajno 1983; London, Taam & Howard 1984, 1986; Ebisuzaki & Nomoto 1986) and attempts have been made to apply model-atmosphere calculations to relate observed fluxes and spectral shapes to angular radii (see e.g. Sztajno et al. 1987; Taam & Fujimoto 1986). Recent results by Penninx et al. (1989) and Damen et al. (1989a) show that current model calculations of burst spectra are too incomplete to lead to useful constraints on the mass-radius relation of neutron stars.

X-ray bursts provide, in principle, other ways to constrain the mass-radius relation of neutron stars through a measurement of the gravitational redshift factor. First, if a discrete feature (a spectral line, or an absorption/emission edge) is present in a spectrum during times that the radiation comes from the neutron star surface (i.e. not during photospheric radius expansion, see below), and if this feature can be identified, one has a direct measurement of the gravitational redshift \(1 + z_\ast\) of the neutron star and thus (see eq. 2) of \(M/R_\ast\). Absorption lines at 4.1 ± 0.1 keV have been reported in bursts from 1636-53 (Waki et al. 1984), 1608-52 (Nakamura et al. 1988), and 1747-214 (Magnier et al. 1989). If the 4.1 keV line is due to helium-like iron, as suggested by Waki et al. (1984), \(1 + z_\ast \sim 1.6\); this seems rather high, but it is perhaps not impossible. Magnier et al. (1989) have shown that the observed equivalent widths would require that the iron abundance is at least \(\sim 10^2\) times higher than the cosmic abundance; this casts doubt on the iron-line interpretation (see also Madej 1989). Furthermore, since during their lifetime as an X-ray source neutron stars in low-mass X-ray binaries are likely to accrete more than a tenth of a solar mass, it would seem unlikely that for all three sources the gravitational redshift, and thus \(M/R_\ast\), would be the same within 2%. An alternative explanation given by Fujimoto (1985), involving transverse Doppler shifts of the emitting material can now be dismissed as it requires a special geometry which is unlikely to occur by chance in three systems (Magnier et al. 1989).

Emission lines have also been observed during \(\gamma\)-ray bursts which have been interpreted as gravitationally redshifted 511 keV annihilation lines emitted from the surface of neutron stars (Mazets et al. 1981; for a review see Liang 1986). If these interpretations are correct, the redshift factors for these neutron stars are \(\sim 1.25 - 1.35\).

A second method to determine the gravitational redshift from observations of X-ray bursts is based on the fact that during some very strong X-ray bursts the photosphere of the neutron star expands as a result of radiation pressure (Tawara et al. 1984; Lewin, Vacca and Basinska 1984). According to model calculations, during the expansion and contraction phase of the photosphere, the luminosity remains within a few percent of the Eddington luminosity (Kato 1983; Ebisuzaki, Hanawa and Sugimoto 1983; Paczynski 1983; Paczynski and Anderson 1986). The Eddington luminosity as observed by a distant observer is given by:

\[
L_{\text{Edd}} = \frac{4\pi cGM}{\kappa} \sqrt{1 - \frac{2GM}{Rc^2}} = 4\pi d^2 \xi F_{\text{Edd}}
\]

(7.3)

Here \(F_{\text{Edd}}\) is the bolometric flux measured by a distant observer during the Eddington luminosity phase, and \(\kappa\) is the electron scattering opacity, which depends on the chemical composition through the expression \(\kappa \approx 0.2(1 + X)\) cm\(^2\) g\(^{-1}\). Here \(X\) is the
fractional hydrogen abundance by mass; thus, $\kappa \sim 0.34$ cm$^2$ g$^{-1}$ for matter with a cosmic abundance, and $\kappa \sim 0.2$ cm$^2$ g$^{-1}$ for hydrogen-poor matter. Notice that $R$ is not equal to the neutron star radius $R_*$, but it is the radius of the photosphere (measured by a local observer) which at maximum expansion can be many times the stellar radius (Tawara et al. 1984; Lewin, Vacca and Basinska 1984; Vacca, Lewin and Van Paradijs 1986; Haberl et al. 1987).

As pointed out by Paczynski and Anderson (1986), and Van Paradijs and Lewin (1988) the dependence of $F_{\text{Edd}}$ on radial distance from the neutron star provides a method to determine the gravitational redshift at the neutron star surface which has the attraction that it may not be hampered by our limited knowledge of how to convert the observed colour temperature to the effective temperature.

In this paper we attempt to apply this method to bursts with photospheric radius expansion observed with EXOSAT from the sources 0748-676, 1636-53, 1735-44, and 1820-30. Although we come to the conclusion that systematic effects presently prevent us from putting significant constraints on neutron star properties, we think that the method is of sufficient interest to warrant a detailed description here.

The application of the method is described in Section 2. We briefly discuss the observations and data analysis in Section 3 (these data have been used before for other purposes; see Sztajno et al. 1985; Lewin et al. 1987; Haberl et al. 1987; Gottwald et al. 1986; Van Paradijs et al. 1988). We discuss the results in Section 4. Our conclusions are summarized in Section 5.

### 7.2 Method

In this section we describe in detail the procedure that we used in deriving the gravitational redshift. In its simplest version it is based on the fact that if the flux is measured during the part of the expansion phase where $R \gg R_*$, the gravitational redshift factor is 1.0 to good approximation, and one finds:

$$L_{\text{Edd}} \approx \frac{4\pi cGM}{\kappa} = 4\pi d^2 \xi F_{\text{Edd}}(R \gg R_*)$$

(7.4)

When the radius of the photosphere just at the end of the contraction phase (we call this ‘touchdown’) is again $R_*$, the luminosity is still Eddington limited, and we have:

$$L_{\text{Edd}} = \frac{4\pi cGM}{\kappa} \sqrt{1 - \frac{2GM}{R_* c^2}} = 4\pi d^2 \xi F_{\text{Edd}}(R = R_*)$$

(7.5)

One should note that $F_{\text{Edd}}(R \gg R_*)$ in eq. (4) is the observed Eddington flux when the radius expansion is large, whereas $F_{\text{Edd}}(R = R_*)$ in eq. (5) is the observed Eddington flux when the photospheric radius is $R_*$; a measurement of these two values of $F_{\text{Edd}}$ leads immediately [by dividing eq. (5) by eq. (4)] to the gravitational redshift from the neutron star surface, and thus to $M/R_*$ (see Fig. 7.1). We have here assumed that if the burst emission is anisotropic, this anisotropy remains constant throughout the burst; this may not always be the case (see e.g. Melia 1987). Furthermore, we have assumed that the opacity $\kappa$ remains the same throughout the burst; as we discuss in Section 4 in more detail there is evidence that this assumption is not always correct.
X-ray bursts and the gravitational redshift of neutron stars

Figure 7.1 Schematic diagram of bolometric flux $F_\infty$ versus colour temperature $kT_\infty$, both as measured by a distant observer, showing the principles of the proposed method. The line running from lower right to upper left (‘cooling track’) is for a spherical blackbody of constant radius; the slope of this line is equal to 4. The dashed line indicates the relation for a blackbody of 2.5 times larger radius. Two ‘touchdown points’ have been indicated on the cooling track, at which the luminosity equals the Eddington limits for cosmic and for hydrogen-poor composition, respectively. Starting from these two points radius expansion tracks have been drawn. The ratio of the redshifts during radius expansion and on the neutron star surface (assuming no changes in chemical composition occur) has been indicated with the arrowed line.

A complication arises from the fact that during the bursts that we use in our analysis the photospheric radius does not necessarily expand by a very large factor, and the approximation that the gravitational redshift factor becomes unity is too crude. Therefore, the ratio of the Eddington fluxes $F_{\text{Edd}}(R > R_*)$ and $F_{\text{Edd}}(R = R_*)$, as observed during radius expansion and at touchdown, respectively, is not $1 + z_\infty$, but instead $(1 + z_\infty)/(1 + z_R)$. We call this ratio $\zeta_\infty$. Thus:

$$
\zeta_\infty = \frac{F_{\text{Edd}}(R > R_*)}{F_{\text{Edd}}(R = R_*)} = \frac{1 + z_\infty}{1 + z_R}
$$

$$
= \frac{1 - \frac{R}{R_*}}{1 - \frac{R}{R_*}} = \frac{1 - \frac{R}{xR_*}}{1 - \frac{R}{R_*}}
$$

(7.6)

where we have introduced $\chi$ as the ratio of the photospheric radius during expansion
7.2. Method

to the neutron star radius (both as measured by local observers). From this expression we obtain the gravitational redshift factor at the neutron star surface by

$$(1 + z)^2 = \frac{\chi^2 - 1/\chi}{1 - 1/\chi}$$

(7.7)

Observable is not $\chi$ but $\chi_\infty$, which is the ratio of radii observed (by a distant observer) during radius expansion and at touchdown, respectively. In case the burst spectra were Planckian, we would find, using eqs (2) and (6), that $\chi_\infty$ is related to $\chi$ by:

$$\chi = \chi_\infty \zeta_\infty$$

(7.8)

Although burst spectra have in general a Planckian shape, model calculations show that the fitted colour temperature, $T_{\text{coo}}$, can differ substantially from the effective temperature, $T_{\text{eff}}$, (London, Taam and Howard 1984, 1986; Ebisuzaki and Nomoto 1986). The ratio $t_\infty = T_{\text{coo}}/T_{\text{eff}}$, is not affected by redshift. Model atmosphere calculations for burst spectra emitted during photospheric radius expansion have not been made so far. We have investigated the sensitivity of the results to the deviations of a burst spectrum from a blackbody by making two different assumptions about the relation between colour and effective temperatures. In the first case we assumed that during radius expansion the ratio $T_{\text{coo}}/T_{\text{eff}}$ remains constant, and therefore $\chi_\infty = \chi_{\text{bcoo}}$. Alternatively, we assumed that during radius expansion the dependence of the ratio $t_\infty$ on $T_\infty$ is the same as during the cooling phase. Then the relation between $\chi_\infty$ and the ratio, $\chi_{\text{bcoo}}$, of the corresponding blackbody radii measured by a distant observer, is:

$$\chi_\infty = \chi_{\text{bcoo}} \left( \frac{t_\infty(R > R_\star)}{t_\infty(R = R_\star)} \right)^2$$

(7.9)

During the cooling phase of the burst, $T_{\text{eff}}$ is proportional to the $1/4$ power of the bolometric flux $F_\infty$, and, therefore, $t_\infty$ is then proportional to the quantity $T_{\text{coo}}/F_\infty^{1/4}$. The observed variation of $T_{\text{coo}}/F_\infty^{1/4}$ with $T_{\text{coo}}$ for the four burst sources, we discuss in this paper, is shown in Fig. 7.3. The ratio $t_\infty(R > R_\star)/t_\infty(R = R_\star)$ can be obtained from this relation together with the values of $T_{\text{coo}}$ as observed during radius expansion and at touchdown.

The above correction for the difference between colour temperature and effective temperature is only useful if a blackbody fit to the spectrum gives a good result. If the shape of the spectrum deviates substantially from that of a Planck curve, one can question the validity of the derived value of the colour temperature, the bolometric correction and $\chi_\infty$. In the next section we show that this is the case in at least one of the sources.

To summarize, our derivation of the gravitational redshift comprises four steps. (i) Determine the ratio, $\chi_{\text{bcoo}}$, of the blackbody radii at some instant during radius expansion and at touchdown, (ii) from the observed colour temperatures during radius expansion and at touchdown derive the ratio $t_\infty(R > R_\star)/t_\infty(R = R_\star)$, where $t_\infty$ stands for the ratio $T_{\text{coo}}/T_{\text{eff}}$, and find $\chi_\infty$ (using eq. 9); alternatively, (iii) we assume $\chi_\infty = \chi_{\text{bcoo}}$, (iii) use the observed ratio, $\zeta_\infty$, of Eddington fluxes to derive $\chi$ (eq. 8), and (iv) finally, the values of $\chi$ and $\zeta_\infty$ together determine the gravitational redshift factor (eq. 7).
Table 7.1 Observational Data on Radius Expansion Bursts observed with EXOSAT.

<table>
<thead>
<tr>
<th>Source</th>
<th>Date</th>
<th>Burst Onset (UT)</th>
<th>Time Resolution (s)</th>
<th>Halves on/off source</th>
<th>Notes</th>
</tr>
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<td>off</td>
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<td>off</td>
</tr>
<tr>
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<td>1.0000</td>
<td>off</td>
<td>on</td>
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<tr>
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<td>off</td>
<td>on</td>
</tr>
<tr>
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<td>0.3125</td>
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<td>on</td>
</tr>
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<td>on</td>
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<td>on 1 detector off</td>
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*The EXOSAT ME detector array consisted of two halves which could be offset from the satellite pointing position by up to 2°.

7.3 Observations and data analysis

EXOSAT data were used of 21 bursts with photospheric radius expansion from four burst sources (see Section 1). The data were collected with the argon counters of the medium-energy (ME) detector array (Turner et al. 1981). Table 7.1 lists for each of the radius expansion bursts the time of burst onset, and the time resolution of the data. Ten of the bursts were observed with the full ME array pointed at the source while for the others one half array was offset by 2° to monitor the background.

Spectra were created for each burst binned in 32 or 64 pulse-height analyzer channels, depending on observation mode. The highest possible time resolution was used in our analysis until the burst flux dropped significantly from its peak (< 20% of the peak value). Persistent emission was subtracted according to the method described e.g. by Sztajno et al. (1985). For all bursts, except three, the persistent emission was obtained during time intervals between ~ 100 s to 500 s prior to the burst. For two bursts from 1820-30 the persistent spectra were accumulated for only 200 s and
130 s, since these bursts occurred just after an interruption of the observations. For one burst from 1735-44 which came only 65 s after the start of an observation, the persistent spectrum was accumulated during 300 s after the burst. This persistent spectrum was compared with several short spectra before and after the burst; they did not differ significantly.

A blackbody function was fitted to the burst spectra with the colour temperature $T_{\text{coo}}$ and a normalization constant as free parameters. A low-energy cut off due to interstellar absorption was included with the following values for the equivalent hydrogen column densities $N_H$: 0.0 for 0748-676 (Schmidtke and Cowley 1987); $5.6 \times 10^{21}$ cm$^{-2}$ for 1636-53 (Lawrence et al. 1983; Sztajno et al. 1985); $8 \times 10^{20}$ cm$^{-2}$ for 1735-44 (Van Paradijs et al. 1988); $1.5 \times 10^{21}$ cm$^{-2}$ for 1820-30 (Vacca, Lewin and Van Paradijs 1986; Haberl et al. 1987). The bolometric flux $F_\infty$ was determined by applying a bolometric correction (which depends only on the fitted temperature) to the flux observed in a finite energy interval (typically 1.5–15 keV). At high radius expansion, only a small part of the spectrum falls within the EXOSAT energy window (the peak of the blackbody function falls in the first or second detector channel). As a result, the bolometric correction is very sensitive to systematic errors in the fitted colour temperature and in the assumed value for the interstellar low-energy absorption. Therefore we have not used burst spectra with $kT_{\text{coo}} < 1$ keV in the determination of the gravitational redshift.

A complication arises from the fact that the spectra during radius expansion can deviate substantially from a Planckian curve: they show an excess above the blackbody fit both at low energies ($E \leq 3$ keV) and at high energies ($E \geq 7$ keV), where they appear to be better described by power laws. This effect is most pronounced in 1820-30, which shows the clearest radius expansion of the four sources. The excess at high energies might be due to systematic uncertainties in the instrumental calibration (A. Parmar, private communication; see also Damen et al. 1989c). However, the high-energy excess observed ($\sim 3\%$ of the total count rate in the spectrum) is much higher than expected from instrumental effects ($\leq 1.0\%$), and starts at lower energies ($\sim 7$ keV compared to $\sim 10$ keV for the instrumental effect). It is therefore very likely that the observed excesses are real. Because of these excesses the fitted colour temperature, the bolometric correction and the derived value of $\chi_{4\times}^{2\infty}$ may be systematically wrong. We have estimated the systematic error in the bolometric correction by fitting power law models to the low- and high-energy parts of the spectrum and using the resulting power law indices to estimate the flux below 1.4 keV and above 15 keV (the energies of the lowest and highest EXOSAT channel used). This method yields a value for the bolometric flux correction, which, of course, depends strongly on the fact that power laws fitting the observed spectra within the EXOSAT energy window are assumed to extend to $E = 0$ keV and $E \rightarrow \infty$, respectively. Using this method we estimate that with the blackbody assumption the bolometric flux during radius expansion of 1820-30 may have been underestimated by 15 – 50% due to the low-energy excess, and by 5 – 30% due to the high-energy excess. The low-energy excess tends to become less near the touchdown point, while the high-energy excess remains approximately constant over the entire radius expansion track. The combined low- and high-energy excesses may result in an underestimation of the bolometric flux by a factor 1.2 – 1.8.
X-ray bursts and the gravitational redshift of neutron stars

Since during photospheric radius expansion the burst luminosity equals the Eddington limit, it is not clear that accretion can then occur (Paczynski, private communication). If accretion were to be interrupted during the radius expansion bursts one would expect the persistent emission to decrease by a substantial amount; even in case the accretion continued during the radius expansion burst, the resulting persistent X-ray emission may be substantially decreased because it is generated inside the optically thick outflowing wind (D. Lamb, private communication). Therefore, the standard procedure of subtracting the persistent emission from the total signal may lead to an underestimate of the burst flux during radius expansion. This effect is therefore expected to lead to an underestimate of the gravitational redshift factor. Since the ratio of the persistent flux to the maximum burst flux during radius expansion varies between $\sim 0.05$ (for 1636-53 and 0748-676), and $\sim 0.25$ (for 1735-44; Van Paradijs, Penninx and Lewin 1988) this effect may not be negligible compared to the required accuracy of the redshift to make a meaningful comparison with neutron star models.

To search for evidence for a reduction of the persistent emission during the expansion phase we used the fact that at very large radius expansion the blackbody temperature of the burst signal becomes low ($<1$ keV in some cases), and the expected contribution of the burst to the total flux becomes very small for photon energies above $\sim 10$ keV. Therefore, one would expect the persistent flux to decrease at high photon energies. We have looked for the presence of such decrease in a superposition of the burst light curves for 1820-30 for photon energies between 10 and 20 keV. The average pre-burst persistent count rate (per half array) in the 10-20 keV interval equals $5.0 \pm 0.2$ c/s. From the average burst light curve, selected for data with a fitted blackbody temperature below 0.8 keV, we find that the average count rate in the 10-20 keV interval equals $7.5 \pm 4.0$ c/s. The expected contribution to this count rate from a 0.8 keV blackbody emitter, whose radius equals the value observed during the largest radius expansion, equals 0.4 c/s. This result is inconclusive, though consistent with the expected reduction in the persistent flux.

### 7.4 Determination of the gravitational redshift

A summary of our spectral analysis of the radius expansion bursts is shown in Fig. 7.2, in which for each source the bolometric flux (for assumed blackbody spectra) is plotted as a function of the fitted blackbody temperature (the scales are logarithmic; the plots are analogous to Hertzsprung-Russel diagrams). In most plots the radius expansion track and the cooling tracks are clearly distinguishable.

In Fig. 7.3 we plot the ratio $T_{\text{coo}}/F_{\infty}^{1/4}$ (which for the cooling track is proportional to the ratio of colour temperature to effective temperature) versus the colour temperature $T_{\text{coo}}$, for data points on the cooling track. It appears that the relation between these quantities can be well described by a linear function. From linear least-squares fits (see table 7.2) we find that for all sources the slopes are the same within their ranges of uncertainty. The average value of the slope equals $0.147 \pm 0.016$. (In the case of bursts from 1608-52 a linear relation was not a good description for the $T_c$ dependence of the $T_c/F_c^{1/4}$ variation (see Penninx et al. 1989)).
7.4. Determination of the gravitational redshift

Figure 7.2 Observed diagrams of bolometric flux $F_{\infty}$ versus colour temperature $kT_{\infty}$ for bursts with radius expansion from four sources. (a) EXO 0748-676; (b) 4U/MXB 1636-53; (c) 4U/MXB1735-44; (d) 4U/MXB 1820-30
Figure 7.3 Variation of the ratio $T_{\infty}/F^{1/4}$ as a function of $T_{\infty}$ during the cooling track of the bursts with radius expansion; then this ratio is proportional to the ratio $T_{\infty}/T_{\text{eff} \infty}$. This variation can be well described by a linear function of $T_{\infty}$. The straight lines indicate linear least-squares fits for each of the sources.

As described in Section 2, to determine the gravitational redshift from the radius expansion track we should take the ratio of the observed bolometric flux at $R > R_*$ to the flux at touchdown. Because of the finite photon statistics and time resolution the exact moment of touchdown is difficult to determine for individual bursts. We therefore estimated the flux at touchdown for a given source by taking the average of the bolometric flux for the data points (from all bursts) with the four to six highest values of the colour temperature (see Table 7.2). Since near the touchdown point in the colour-temperature diagram the upward-sloping radius expansion track meets
### Table 7.2 Results of Gravitational Redshift Analysis for the four Sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>$kT_{tdoo}$ (keV)</th>
<th>$F_{tdoo}$ (10^{-8} erg cm^{-2} s^{-1})</th>
<th>$1 + z_<em>$ correction included</em></th>
<th>$1 + z_<em>$ no correction</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>0748-676</td>
<td>2.45</td>
<td>1.92</td>
<td>2.63 (+0.29; -0.33)</td>
<td>2.90 (+0.29; -0.34)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.24</td>
<td>2.29 (+0.25; -0.28)</td>
<td>2.50 (+0.26; -0.30)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.56</td>
<td>2.03 (+0.21; -0.25)</td>
<td>2.18 (+0.24; -0.26)</td>
</tr>
<tr>
<td>1636-53</td>
<td>2.30</td>
<td>5.76</td>
<td>1.06 (+0.16; -0.19)</td>
<td>1.09 (+0.09; -0.10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.09</td>
<td>0.90 (+0.21; -0.28)</td>
<td>0.86 (+0.12; -0.13)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.41</td>
<td>1.20 (+0.25; -0.30)</td>
<td>0.59 (+0.20; -0.31)</td>
</tr>
<tr>
<td>1735-44</td>
<td>2.40</td>
<td>2.16</td>
<td>1.03 (+0.20; -0.26)</td>
<td>1.21 (+0.11; -0.12)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.48</td>
<td>1.31 (+0.22; -0.27)</td>
<td>0.90 (+0.13; -0.14)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.80</td>
<td>1.15 (+0.26; -0.34)</td>
<td>0.53 (+0.19; -0.31)</td>
</tr>
<tr>
<td>1820-30</td>
<td>2.70</td>
<td>4.33</td>
<td>1.12 (+0.07; -0.07)</td>
<td>1.15 (+0.07; -0.07)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.65</td>
<td>1.05 (+0.05; -0.05)</td>
<td>1.02 (+0.06; -0.06)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.97</td>
<td>0.89 (+0.12; -0.12)</td>
<td>0.90 (+0.04; -0.04)</td>
</tr>
</tbody>
</table>

*Correction for the non-Planckian shape of burst spectra [see eq. (9)].

The downward-sloping cooling track this seems a reasonably method to estimate the touchdown flux. In Table 7.2 we give for each source the touchdown temperature, $kT_{tdoo}$, and three values of the touchdown flux, $F_{tdoo}$: the average value and an estimated lower and upper limit for this flux.

For a given value of the bolometric touchdown flux we obtain for each spectrum during radius expansion a value of $(1 + z_*)^2$, using the procedure outlined in Section 2. Clearly, we must restrict the analysis to data on the photospheric radius expansion track for which we selected $\chi_{4\pi\infty} > 1.2$. We treated the error in the touchdown flux differently from those of the other observed quantities since it affects the values of $(1 + z_*)^2$ systematically in the same way (the results are insensitive to changes in the touchdown temperature). We took account of this by propagating the errors in $\zeta_\infty$ and $\chi_\infty$ for a given value of the touchdown flux. The results of this analysis are summarized in Table 7.2 in the form of average values of the redshift and their 1σ error range (they correspond to the square roots of the corresponding values of $(1 + z_*)^2$). In the following we discuss the results for each source individually.

#### 7.4.1 EXO 0748-676

From the temperature-flux diagram of this source (Fig. 7.2) we see that the radius expansion track is very sparsely populated, particularly near the expected location of touchdown. Therefore, the touchdown flux may have been systematically underestimated leading to a systematic overestimate of the redshift. Not much value should therefore be attached to these results (see Table 7.2).
7.4.2 4U/MXB 1636-53

The temperature-flux diagram of 1636-53 (see Fig. 7.2) shows a rather complicated radius expansion track. As described earlier by Sugimoto et al. (1984), early in the bursts the photospheric radius increases rapidly by a factor $\sim 3$, then, as the radius reaches its maximum value and also during the subsequent contraction of the photosphere, the flux increases by somewhat less than a factor two. It was suggested by Sugimoto et al. (1984) that this flux increase is the result of the ejection of a hydrogen-rich outer envelope; the subsequent exposure to the surface of hydrogen-poor matter, whose nuclear composition is affected by nuclear processing in the thermonuclear flash, causes an increase of the Eddington limit by a factor $\sim 1.7$. This picture of a change from an Eddington limit for hydrogen-rich matter to one for hydrogen-poor matter is strongly supported by the gap in the distribution of peak fluxes of the bursts from 1636-53 (Sugimoto et al. 1984; Fujimoto and Taam 1986; Lewin et al. 1987; Fujimoto et al. 1988). The peak fluxes of the bursts below the gap are continuously distributed up to a cut-off value of $\sim 3.5 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, those above the gap are consistent with a single value of $\sim 6.0 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. The ratio between these two flux values is consistent with the ratio of the Eddington luminosities of hydrogen-poor and cosmic composition. This peak flux distribution can be explained as follows: weak bursts do not reach the hydrogen-rich Eddington limit. As soon as they are strong enough a stellar wind is created which leads to envelope ejection (Ebisuzaki et al. 1983; Kato 1983; Paczynski 1983). As long as the outermost layers are not completely blown off, or not affected by mixing with the products of the thermonuclear flash, the peak flux remains at the hydrogen-rich Eddington limit. As soon, however, as the hydrogen content of the outermost layers decreases the Eddington limit increases; when the hydrogen-rich layers are completely ejected (for the strongest bursts) the peak flux is given by the hydrogen-poor Eddington limit. Apparently, the chance of encountering a burst with a peak flux inside the gap is small (one such burst has been found by Damen et al. 1989b). This may be related to a sharp transition in the composition of the neutron star envelope (D. Lamb, private communication). It should be noted that no gap has been observed in the peak flux distribution of some other well-studied burst sources (e.g. 1728-34, see Basinska et al. 1981).

Because of the above composition change during the photospheric radius expansion we have in our estimate of the redshift used only data points on the radius expansion track after the helium Eddington limit has been reached (this corresponds to approximately $kT_{\infty} > 1.82$ keV). The radius expansion track of 1636-53 that remains, is short ($\chi^{2}_{4\infty} < 1.5$). The redshifts we derive are rather small (see Table 7.2). Since it is not clear whether the composition remains hydrogen poor during the contraction phase, these results must at this time be considered as rather uncertain in a systematic way. In particular, the combined uncertainty in (i) the touchdown flux, (ii) the variation of the composition during radius contraction and (iii) the relation between colour and effective temperature, does not exclude a redshift factor of 1.6, as has been inferred from the 4.1 keV absorption feature observed in some burst spectra from 1636-53 (Waki et al. 1984). To illustrate this, we take the touchdown point at $kT_{\infty} = 2.3$ keV, and $F_{\infty} = 5.76 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ (the latter value is rather low but cannot be excluded by our data, see Fig. 7.2). For the point on the radius
expansion track where the hydrogen has just disappeared we take: $kT_{\infty} \sim 1.8$ keV, $F_{\infty} = 6.4 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ (the corresponding value of $\chi_{k\infty} = 1.68$). Using eq. (7) with $(1 + z_*) = 1.6$, we find $\chi_{\infty} = 1.18$. Thus, with eq. (9) we find that for a gravitational redshift $(1 + z_*) = 1.6$ the ratio of colour temperature to effective temperature would have to decrease by a factor $\sim 0.84$ when the colour temperature changes from $kT_{\infty} = 2.3$ keV to 1.8 keV. There are presently no reasons to exclude this.

**7.4.3 4U/MXB 1735-44**

The flux-temperature diagram of this source shows a rather short $(\chi_{k\infty} < 3)$ radius expansion track, which appears reasonably well defined in spite of the fact that it is sparsely populated (see Fig. 7.2). The accuracy with which the touchdown flux can be determined is somewhat adversely affected by one high point along the cooling track. The resulting values of the gravitational redshift are not very accurate, and do not put significant constraints on neutron star properties.

**7.4.4 4U/MXB 1820-30**

All bursts from this source observed with SAS-3 and EXOSAT show radius expansion (Vacca, Lewin & Van Paradijs 1986; Haberl et al. 1987). For the purpose of determining the gravitational redshift of a neutron star this source is of particular interest because its 11 minute orbital period indicates that the mass transferring companion star is hydrogen poor (Verbunt 1987; Rappaport et al. 1987). Therefore, the opacity should remain the same throughout the radius expansion. In the flux-temperature diagram of this source (Fig. 7.2d) the radius expansion shows up clearly as a long $(\chi_{k\infty}$ up to 20), approximately horizontal track. The very strong radius expansion and the constancy of the composition make this a potentially very good source for a redshift determination.

At very low temperature $(kT_{\infty} < 1$ keV) the track curves downward, i.e. the bolometric flux decreases for increasing photospheric radius. As pointed out in Section 3, this is likely due to the fact that at these large radii the peak of the Planck function falls in the first or second energy channel of the ME detector, and therefore the bolometric correction is very sensitive to small systematic errors in the fitted temperature and in the value assumed for the interstellar low-energy absorption. We have not used the burst spectra with $kT_{\infty} < 1$ keV in the determination of the gravitational redshift.

Near touchdown, the radius expansion track seems to widen; this causes a systematic uncertainty in the touchdown flux which is substantially larger than the formal uncertainty derived according to the method described above. Therefore, the rather low redshift derived for 1820-30 (see Table 7.2) is not reliable.

Because there is no formal model available with which to compare the distribution of points in the flux-temperature diagram, it is very hard to derive a formal error on the observed value of the touchdown flux. However, from Fig. 7.2 it appears highly unlikely that the touchdown flux is less than $3.6 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. Thus it would appear that we can put at least an upper limit on the gravitational redshift. A comparison with the flux $(4.60 \pm 0.06 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1})$ on the radius expansion
track near $kT_{\infty} \sim 1.2$ (corresponding to $\chi_{h\infty} \sim 6$) indicates that $1 + z_* < 1.33$. From Table 7.2 we infer that the redshift values for 1820-30 are not much affected by the uncertainty on the variation of the ratio of colour to effective temperature along the radius expansion track. Since the accreted matter in 1820-30 is hydrogen poor, systematic uncertainty due to unknown composition changes (which in other sources causes an uncertainty by a factor up to 1.7) should not affect the redshift values either. With a persistent flux of 8% of that during radius expansion, the third major source of systematic uncertainty, due to a decrease of the persistent emission during radius expansion, can lead to at most an increase of the redshift by 8%. This results in an upper limit of 1.44 to the redshift of the neutron star in 1820-30.

Because of the systematic uncertainty in the bolometric corrections during radius expansion (Section 3) this upper limit is not firm. As discussed in Section 3, during radius expansion (but not at touchdown) the bolometric flux may be underestimated by an uncertain factor, which is probably higher than 1.2, and may be as high as 1.8. This will increase the upper limit on $1 + z_*$ to at least 1.6. Because of the non-Planckian shape of the spectra the fitted colour temperatures, and therefore the derived values of $\chi_{\infty}$ and $1 + z_*$ may become meaningless, unless detailed models of the radiative transfer through the expanding outer layers of a neutron star wind become available.

### 7.5 Conclusion

We have attempted to determine the gravitational redshift from the surface of neutron stars using observations of the variation of the Eddington flux during the phase of photospheric radius expansion in very strong X-ray bursts from four sources.

The method we have used turns out to be very sensitive to several systematic errors; the most important of these are due to possible variations, during the radius expansion, of (i) the photospheric chemical composition, (ii) the persistent emission, (iii) the shape of the burst spectrum. Future studies of neutron star winds during the phase of radius expansion and of accretion onto weakly magnetized neutron stars may lead to trustworthy estimates of these effects.

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### References


X-ray bursts and the gravitational redshift of neutron stars


