A study of x-ray bursts with EXOSAT
Damen, E.M.F.

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Chapter 6

Constraints on the inner accretion flow of 4U/MXB 1636–53 from a comparison of X-ray burst and persistent emission


Summary

We present a detailed analysis of the importance of Comptonization in burst and persistent spectra of the low-mass X-ray binary 4U/MXB 1636–53, and infer from this analysis that the inner accretion flow is geometrically thin.

The observations we used were made with the EXOSAT ME instrument between 1983 and 1985. We find that burst spectra of 1636–53 are very nearly Planckian in shape; from an upper limit to a high-energy excess in these spectra we infer that the Thomson scattering optical depth of a possible intervening hot cloud must be less than 1 during bursts, and that the Compton y parameter of that cloud must be less than 0.5. During persistent emission, which – according to our models – originates from a medium of small absorption optical depth, we infer a Thomson optical depth of 4–8, an electron temperature of 2–5 keV, and a value of 0.8–1.1 for y.

The large difference between the Comptonization parameters during bursts and persistent emission implies that the inner accretion flow is geometrically thin at persistent luminosities of 0.02–0.055 times the critical Eddington luminosity, and remains geometrically thin when irradiated by bursts of radiation from the neutron star with peak luminosities up to at least 0.8 \( L_E \).

Key Words: accretion disks, stars:binaries:close, stars:neutron, X-rays:binaries, X-rays:bursts

6.1 Introduction

The spectrum of an X-ray burst can generally be approximated quite well by a black-body model. However, numerical model calculations of the radiative transfer in neutron star atmospheres show that, although the shape of the spectrum is very nearly
Planckian, the temperature fitted to the spectrum (i.e. the colour temperature, $T_c$) can deviate substantially from the effective temperature, $T_{\text{eff}}$, of the neutron star atmosphere, with values of the ratio $T_c/T_{\text{eff}}$ as high as 1.6 (London, Taam and Howard 1984, 1986; Sunyaev and Titarchuk 1986, Foster, Ross and Fabian 1986, Ebisuzaki and Nomoto 1986, Madej 1989).

Observational evidence that burst spectra deviate from blackbody spectra has come from two directions: firstly, from observations of bursts from 1636–53 and 4U 1608–52 (Matsuoka 1986) and EXO 0748–676 (Gottwald et al. 1986), it appears that not all bursts from a single source follow the same relation between colour temperature and bolometric flux. Secondly, Damen et al. (1989) recently found that the variations in this relation are correlated with the duration of the bursts. This correlation suggests a link between properties of the bursting layer (e.g. its chemical composition), and the neutron star atmosphere where the observed spectrum is formed.

Nakamura et al. (1989) found that time-resolved burst spectra from 1608–52 show a high-energy excess (above 10 keV) relative to the fitted blackbody spectrum. This excess was observed only when the persistent luminosity of the source was low ($<10^{37}$ erg s$^{-1}$) and disappeared when the persistent luminosity was high. The excess in these burst spectra is very apparent at low colour temperatures ($kT_c < 1.5$ keV, i.e. in the decay part of bursts) and it disappears as $T_c$ rises. Nakamura et al. argue that the most likely explanation for this excess is the presence of a cloud around the source with an electron temperature of about 100 keV, in which photons of relatively low energy are up-scattered to higher energies (i.e. above 10 keV) by inverse Compton scattering; they use a Comptonized blackbody model to fit the burst spectra, keeping the electron temperature in the Comptonizing cloud, $kT_c$, fixed at 100 keV. Fitted values for the Compton $y$ parameter range from 0.2 for spectra with a colour temperature $kT_c \sim 1.2$ keV to 0.0 for the high-temperature spectra ($kT_c \sim 2$ keV) (see Section 6.4.3 for a definition of the Compton $y$ parameter).

These results show that detailed spectral analysis of bursts may reveal properties of the immediate surroundings of the neutron star. The spectral energy distribution of the persistent emission is another source of information about the structure of the neutron star environment (accretion disk, accretion disk corona, boundary layer). Frequently used models for the spectra of the persistent X-ray emission include: (i) optically thick blackbody radiation from the accretion disk with the temperature decreasing from the inner edge outwards (Mitsuda et al. 1984, hereafter called multi-temperature blackbody model); (ii) blackbody emission modified by electron scattering (Shakura and Sunyaev 1973); (iii) Comptonization dominated emission (Sunyaev and Titarchuk 1980, hereafter called the Sunyaev-Titarchuk model). White, Stella and Parmar (1988) find that the persistent spectra of ten luminous non-pulsating low-mass X-ray binaries are best fitted with the latter model, with optical depths for the Comptonizing cloud of $\tau \sim 15$ and a value of $y$ between 2 and 4. Their fits require an additional blackbody component of temperature $kT_c \sim 1.3$ keV for spectra of the most luminous sources. They propose that this blackbody component comes from the boundary layer between the accretion disk and the neutron star surface.

The aim of this paper is to assemble information about the inner accretion flow from both the burst spectra and the persistent spectra of the low-mass X-ray binary
Table 6.1 Overview of all EXOSAT ME observations of 4U/MXB 1636–53.

<table>
<thead>
<tr>
<th>obs. start (UT)</th>
<th>obs. end (UT)</th>
<th>number of bursts</th>
<th>Previous analysis of bursts</th>
</tr>
</thead>
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<tr>
<td>1984 May 05 23:40</td>
<td>1984 May 06 20:55</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>1984 May 08 09:08</td>
<td>1984 May 09 10:04</td>
<td>8</td>
<td>Sztajno et al. (1985)</td>
</tr>
<tr>
<td>1984 Sep 07 04:59</td>
<td>1984 Sep 07 12:05</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1985 Sep 05 06:20</td>
<td>1985 Sep 06 05:56</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>1985 Sep 06 16:16</td>
<td>1985 Sep 06 20:42</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

1636–53. We report an upper limit to the presence of a high-energy excess in the burst spectra in Section 3. In Section 4 we use that upper limit, with the help of Monte Carlo simulations of Comptonized blackbody spectra, to derive constraints on the properties of the Comptonizing cloud that may surround the neutron star during bursts. In Section 5 we discuss a model for the persistent emission and use it to derive parameters of a Comptonizing medium that is the source of that emission. In Section 6, we compare the results of the two previous Sections and discuss the implications of our findings for our knowledge of the inner accretion flow. We summarize our conclusions in Section 7.

6.2 Observations

The observations of 1636–53 which we used in our analysis have been made with the Medium Energy (ME) detectors of EXOSAT (Turner, Smith and Zimmermann 1981) between 1983 and 1985. The total duration of these observations is ~ 180 hours. During these observations 61 bursts were recorded from the source. In Table 6.1 we list the observation times and the number of bursts in each observation, together with references to previous analyses of these bursts. Two bursts have been excluded from the sample used in this work, as no suitable data are available for them. Some bursts showed an expansion of the photosphere, which occurs if the luminosity reaches the Eddington limit. The Eddington flux of the source is therefore known to be $6.5 \pm 0.5 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. During the observations the persistent flux of the source varied between $\sim 1.3 \times 10^{-9}$ and $\sim 3.6 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ (in the photon energy range 1.5–15.0 keV), and showed rather small variations on time scales of a few hours. For previous studies of the persistent emission we refer to Breedon et al. (1986), Vacca et al. (1987) and White, Stella and Parmar (1988).
6.3 Analysis of the burst spectra

6.3.1 Spectral fits

We accumulated burst spectra over time intervals which varied between ~ 1s near the peak of the bursts and 10 – 20s near the end of the bursts. The average number of spectra per burst is 16. A spectrum of persistent emission plus background was accumulated (for 100s) just prior to every burst, and subtracted from the burst spectra. To account for the calibration uncertainty of the EXOSAT ME instrument, a 1 percent extra uncertainty has been added quadratically to the random noise errors on the observed spectrum before fits were made. All spectra have been fitted with a blackbody model which includes a correction for a low-energy cut off due to interstellar absorption with a fixed value for the equivalent hydrogen column density $N_H$ of $56 \times 10^{20}$ cm$^{-2}$, as derived from optical observations of the source (Gorenstein 1975, Lawrence et al. 1983). The resulting fitted colour temperature, $T_c$, is then used to calculate a bolometric correction, to convert the observed flux in a limited passband to the bolometric flux at any point in time during the burst.

Each of the approximately 900 spectra thus obtained did not individually have sufficiently low random noise to search for small deviations from a blackbody spectral shape in a statistically meaningful way. We therefore improved statistics by constructing means of small groups of spectra. The subdivisions of our sample were made using both the bolometric flux of the spectrum and another property of the burst as selection criteria. We used 10 bolometric flux groups. As a second criterion, to further subdivide the groups of equal flux, we tried three burst properties. In this manner we obtained three sets of mean spectra, each of which is based on all 900 individual spectra. The three burst properties used as the second selection criterion are:

(a) The position of the cooling track of the burst from which the spectrum has been sampled in a diagram of bolometric flux vs. fitted colour temperature (four subgroups). This position, expressed by the value of the colour temperature at 10% of the Eddington flux, $kT_{0.1}$, is not the same for all bursts from 1636–53 (see Damen et al. 1989).

(b) The level of persistent emission prior to the burst (four subgroups).

(c) The time of the observation of the burst (ten subgroups; we do not expect a physical connection between the time of the burst and its properties, but slow changes in instrumental properties could show up here).

For details on these criteria we refer to Table 6.2.

The mean spectra of each subgroup in each of the three sets have been fitted with a blackbody model. In the fits, the parameter $N_H$ was not fixed, to prevent possible systematic effects at high energies. These effects may occur because an inaccurate value for $N_H$ can give rise to a bad fit at low energies ($E < 2$ keV), which is compensated in the fit procedure at higher energies. The resulting fits to the mean spectra are usually not good (reduced $\chi^2 \gtrsim 2$ for $\sim 25$ degrees of freedom). This
6.3. **Analysis of the burst spectra**

### Table 6.2 a

<table>
<thead>
<tr>
<th>$F_{bol}$ a</th>
<th>Excess$^b$ between 11.7 and 19.8 keV</th>
</tr>
</thead>
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<td>(1)</td>
</tr>
<tr>
<td>0.10 - 1.00</td>
<td>2.2 ± 0.7</td>
</tr>
<tr>
<td>1.00 - 2.00</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>2.00 - 4.00</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>4.00 - 6.00</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>6.00 - 9.00</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>9.00 - 12.00</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>12.00 - 15.00</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>15.00 - 20.00</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>20.00 - 45.00</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>45.00 - 70.00</td>
<td>0.6 ± 0.1</td>
</tr>
</tbody>
</table>

$^a$In $10^{-9}$ erg cm$^{-2}$ s$^{-1}$

$^b$Percentage of total counts in mean spectrum.

(1) $kT_{bol} = 1.04 - 1.17$ keV.

(2) $kT_{bol} = 1.17 - 1.22$ keV.

(3) $kT_{bol} = 1.22 - 1.36$ keV.

(4) $kT_{bol} = 1.36 - 1.60$ keV.

### Table 6.2 b

<table>
<thead>
<tr>
<th>$F_{bol}$ a</th>
<th>Excess$^b$ between 11.7 and 19.8 keV</th>
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</thead>
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<tr>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>0.10 - 1.00</td>
<td>0.6 ± 0.5</td>
</tr>
<tr>
<td>1.00 - 2.00</td>
<td>0.7 ± 0.3</td>
</tr>
<tr>
<td>2.00 - 4.00</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>4.00 - 6.00</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>6.00 - 9.00</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>9.00 - 12.00</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>12.00 - 15.00</td>
<td>0.2 ± 0.1</td>
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<tr>
<td>15.00 - 20.00</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>20.00 - 45.00</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>45.00 - 70.00</td>
<td>0.3 ± 0.2</td>
</tr>
</tbody>
</table>

$^a$In $10^{-9}$ erg cm$^{-2}$ s$^{-1}$

$^b$Percentage of total counts in mean spectrum.

(1) persistent flux = $1.2 - 1.8 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$.

(2) persistent flux = $1.8 - 2.3 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$.

(3) persistent flux = $2.3 - 2.7 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$.

(4) persistent flux = $2.7 - 4.0 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$.
Table 6.2 c

<table>
<thead>
<tr>
<th>$F_{bol} \text{a}$</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
<th>(7)</th>
<th>(8)</th>
<th>(9)</th>
<th>(10)</th>
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</thead>
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<tr>
<td>0.10 – 1.00</td>
<td>—</td>
<td>-3.8 ± 1.3</td>
<td>—</td>
<td>4.1 ± 3.1</td>
<td>—</td>
<td>1.5 ± 1.5</td>
<td>0.5 ± 0.7</td>
<td>0.4 ± 0.4</td>
<td>2.1 ± 0.6</td>
<td>-0.5 ± 0.5</td>
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<td>-0.2 ± 0.6</td>
<td>0.1 ± 0.6</td>
<td>1.3 ± 0.8</td>
<td>0.4 ± 0.7</td>
<td>0.4 ± 0.5</td>
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<td>2.00 – 4.00</td>
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<td>0.5 ± 0.3</td>
<td>1.4 ± 0.7</td>
<td>0.4 ± 0.3</td>
<td>0.3 ± 0.2</td>
<td>0.2 ± 0.4</td>
<td>0.1 ± 0.2</td>
<td>0.3 ± 0.1</td>
<td>0.8 ± 0.2</td>
<td>0.6 ± 0.2</td>
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<tr>
<td>4.00 – 6.00</td>
<td>0.0 ± 0.2</td>
<td>-0.2 ± 0.2</td>
<td>0.6 ± 0.5</td>
<td>0.2 ± 0.3</td>
<td>0.1 ± 0.2</td>
<td>0.6 ± 0.3</td>
<td>0.3 ± 0.2</td>
<td>0.4 ± 0.1</td>
<td>1.0 ± 0.2</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>6.00 – 9.00</td>
<td>0.4 ± 0.2</td>
<td>0.0 ± 0.2</td>
<td>0.6 ± 0.4</td>
<td>0.5 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>-0.3 ± 0.3</td>
<td>0.1 ± 0.2</td>
<td>0.5 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>9.00 – 12.00</td>
<td>0.5 ± 0.2</td>
<td>0.2 ± 0.1</td>
<td>0.4 ± 0.3</td>
<td>0.2 ± 0.2</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.2</td>
<td>0.4 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>0.5 ± 0.1</td>
<td>—</td>
</tr>
<tr>
<td>12.00 – 15.00</td>
<td>0.4 ± 0.1</td>
<td>1.0 ± 0.3</td>
<td>0.3 ± 0.2</td>
<td>0.4 ± 0.2</td>
<td>0.3 ± 0.2</td>
<td>0.2 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>0.9 ± 0.2</td>
<td>—</td>
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<tr>
<td>15.00 – 20.00</td>
<td>0.1 ± 0.1</td>
<td>—</td>
<td>0.7 ± 0.3</td>
<td>0.6 ± 0.2</td>
<td>0.3 ± 0.1</td>
<td>0.9 ± 0.4</td>
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<td>—</td>
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<td>0.4 ± 0.1</td>
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<td>0.1 ± 0.2</td>
<td>0.3 ± 0.2</td>
<td>—</td>
<td>—</td>
<td>0.6 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>0.4 ± 0.2</td>
</tr>
</tbody>
</table>

aIn $10^{-9}$ erg cm$^{-2}$ s$^{-1}$

bPercentage of total counts in mean spectrum.

(3) observation period: 1984 May 06 01:28 UT–1984 May 06 06:49 UT.
(4) observation period: 1984 May 06 07:09 UT–1984 May 06 20:48 UT.
(5) observation period: 1984 May 08 11:00 UT–1984 May 09 09:29 UT.
(6) observation period: 1984 Sep 07 05:11 UT–1984 Sep 07 12:02 UT.
(7) observation period: 1985 Aug 06 20:01 UT–1985 Aug 07 01:34 UT.
(8) observation period: 1985 Aug 07 12:05 UT–1985 Aug 09 00:02 UT.
(10) observation period: 1985 Sep 05 06:49 UT–1985 Sep 06 20:33 UT.
6.3. Analysis of the burst spectra

Figure 6.1 Excesses in burst spectra. (a) upper panel: Mean observed burst spectrum (Flux interval 15–20 x10^{-9} erg cm^{-2} s^{-1}, kT_{0.1} interval 1.17–1.22 keV), not corrected for interstellar absorption, and fitted blackbody spectrum (dashed line, kT_{fit} = 1.83 keV). lower panel: Residuals of the observed spectrum with respect to the best fit. (b) As (a), for a Comptonized spectrum with a well-resembling excess. This model has y = 0.18, kT_{e} = 60 keV, and kT_{bb} = 2.0 keV. The fitted blackbody has kT_{fit} = 2.13 keV. The error bars would apply if the spectrum had been observed by EXOSAT with a similar count rate and background as the spectrum in panel (a). Numerical errors in the simulation are negligible.

is mainly caused by the fact that the mean spectra show a clear excess at photon energies ≥ 10 keV. Fig. 6.1a shows an example of a mean spectrum and the best fit.

To quantify this high-energy excess, the fit residuals between 11.7 and 19.8 keV have been added and the result has been expressed as a fraction, \( \epsilon \), of the total number of counts in the mean spectrum. Table 6.2 lists the value of \( \epsilon \) for the mean spectra of all subgroups. This table shows that the variation in the observed excess for different mean spectra is not significant. A few apparently high points appear to be the result of background subtraction problems (observations of 1984 May 6, 00^h – 05^h); they were excluded from our results.

Formal straight line fits show that there is no trend of \( \epsilon \) with bolometric burst flux for any of the subgroups of mean spectra selected according to the second selection criteria mentioned above. Moreover, the observed excesses are consistent with a
Constraints on the inner accretion flow of 4U/MXB 1636–53

constant value for $\varepsilon$ of $(4.5 \pm 0.3) \times 10^{-3}$.

6.3.2 The influence of calibration uncertainties

The small observed high-energy excess of $\sim 0.5\%$ of the total count rate in the spectrum is very sensitive to calibration uncertainties of the EXOSAT ME instrument. It is generally assumed that the ME calibration can be trusted down to a level of 1%, below which systematic effects become important. Recently, Drs. F. Haberl and A. Parmar of the EXOSAT observatory at ESTEC and Dr. G. Hasinger of the Max Planck Institut für Extraterrestrische Physik in Garching informed us that the following ME calibration problems have been discovered:

1. Due to position-dependent gain variations of the detectors, a small fraction of the source counts is redistributed in the spectrum, and appears erroneously at high energies. Extensive tests performed at ESTEC, using spectra of 73 sources having a wide range of spectral shapes, show that $\sim 0.1\%$ of the total source counts appears above 30 keV. Determining what fraction appears at lower energies poses the difficulty that more and more ‘real’ source counts appear at these energies. The tests show that in the case of sources with a ‘soft’ spectrum (for which not many ‘real’ source counts are expected at high energies) $\sim 0.2\%$ of the total count rate appears above 20 keV and $\sim 1\%$ appears between 10 and 20 keV. Note that an unknown fraction of these counts are ‘real’ source counts.

How this effect will work out in our analysis is not clear. The ME instrument has been calibrated using the spectrum of the Crab Nebula in such a way that fits this spectrum using a power law spectral model yield the well-established values for the photon index $\Gamma = 2.10 \pm 0.03$, normalization constant $C = 9.7 \pm 1.0$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ (Toor and Seward 1974) and $N_H = (3.45 \pm 0.42) \times 10^{21}$ cm$^{-2}$ (Schattenburg and Canizares 1986). This means that excess counts at high energies due to the instrumental effect are compensated in the calibration, but only for a spectrum having this particular shape. Using this calibration on an arbitrary spectrum will introduce either an excess or a deficiency at high energies, depending on the detailed shape of the spectrum. However, the magnitude of the effect will not be larger than $\sim 1\%$.

To account for this effect in our analysis, we assume the worst case, i.e. we assume that the inferred excess between 10 and 20 keV is underestimated by $\sim 1\%$.

2. Spectra taken from the Crab Nebula show a high-energy excess when fitted with a power law model using the values mentioned above for the photon index, the normalization constant and the equivalent hydrogen column density. This excess is due to non-linearities in the Analogue-Digital Converter (ADC) of the instrument, which introduce a ‘wiggle’ in the fit residuals around 3 keV. This ‘wiggle’ is compensated in the fit procedure at high energies, resulting in an apparent excess above $\sim 10$ keV of $\sim 1\%$ of the total count rate in the spectrum.

Again it is not clear how this effect manifests itself in our blackbody fits, since these spectra differ from that of the Crab Nebula.
In view of these two calibration uncertainties we conclude that the reality of the apparent 0.5% high-energy excess cannot be considered established. Setting the joint effect of the two calibration uncertainties to 1.5% and adding the observed high-energy excess, we set an upper limit of 2% on any high-energy excess in number flux between 11.7 and 19.8 keV in burst spectra from 1636-53, and an upper limit of 1% on any high-energy deficiency in the same photon energy range.

6.4 Comptonization of burst spectra

As mentioned in the Introduction, a high-energy excess in burst spectra may be caused by Compton up-scattering of photons in a hot plasma cloud around the neutron star. To interpret the above-derived upper limit to a high-energy excess in the burst spectra in terms of limits on parameters of such a cloud, we performed Monte-Carlo simulations of this Comptonization process.

6.4.1 Method of computing the Comptonized spectra

Theoretical spectra were computed using a fully relativistic Monte-Carlo simulation of the Compton-scattering of photons that emerge from the neutron star's photosphere. A detailed description of the numerical method we use has been given by Pozdnyakov, Sobol and Sunyaev (1983), so we will here only outline a few key features, especially where they differ from other codes that are frequently used (e.g. Bussard et al. 1988, Loh and Garmire 1971). The code is fully relativistic in its treatment of the photon transport: Klein-Nishina values are used for integrated and differential cross-sections, the electrons are sampled from a relativistic Maxwellian distribution, and the effects of aberration and Doppler shift on the probability for a photon to encounter an electron with a given momentum are accounted for. The gravitational redshift of photons traversing the potential well of the neutron star and stimulated scattering are not included in the model.

Another feature of the code is the way the emergent X-ray spectrum is accumulated: after each scattering, the photon escape probability is computed, but it is not used to determine simply whether the photon either escapes entirely or stays in the cloud. Instead, a fraction of the photon equal to the escape probability is allowed to escape and put into the appropriate emergent spectral bin, whereas the rest of it is used in further scatterings: a position for its next collision is selected subject to the condition that it remain in the cloud. The calculation of a photon path is stopped if the remaining photon weight (initially 1) has decreased below a certain value, usually chosen to be $10^{-4}$. Typically, $5 \times 10^4$ photon paths were used per simulation in the present work to ensure small and reliably computable estimates of the statistical uncertainties of the emergent spectrum.

6.4.2 Model assumptions

The neutron star is assumed to emit photons that have a blackbody distribution with a temperature $T_{bb}$. They are scattered in a cloud of hot gas of Thomson optical depth $\tau$ and electron temperature $T_e$. The cloud is taken to be spherical and homogeneous,
and the neutron star a point source emitting isotropically (a finite sized neutron star would slightly soften the spectrum for a given set of parameters: it would re-absorb some photons, and since these re-absorbed photons have undergone either a large-angle scattering or more than one scattering, they tend to be more energetic than the average photon. However, for a large cloud of small optical depth these effects are negligible, both because the probability of multiple scattering is small and because the angular size of the neutron star, as seen from an average point in the cloud, is small). No attempt was made to constrain the ranges of the three model parameters by making a joint model of the accretion hydrodynamics and its coupling to the radiation field.

6.4.3 The Compton $y$ parameter

It is important to note here that some care is needed in defining the Compton $y$ parameter in terms of an optical depth: $y$ is intended to be a rough measure of the energy gain of photons when they travel through a medium. In the work presented here, we may in first approximation consider both the electron thermal energy $kT_e$ and the photon energy to be much less than the electron rest energy $mc^2$. The estimate is then the product of two factors: The first is the mean fractional energy change per collision. For (inverse) Compton scattering of photons of energies sufficiently less than $kT_e$ (and isotropic distributions of photon and electron momenta), the change is a gain and the amount is $4kT_e/mc^2$. The second is the mean number of collisions. Since the collision cross-section is still near the Thomson value, we may regard it as independent of photon energy. The mean number of collisions is then proportional to the Thomson optical depth $\tau$ or its square, whichever is the greater. In summary,

$$y = \frac{4kT_e}{mc^2} \max(\tau, \tau^2)$$  \hspace{1cm} (6.1)

The upscattering saturates, of course, if the optical depth is such that almost all photons reach an energy of about $3kT_e$. If this is not so, the ingoing and outgoing luminosities are related by:

$$L_{\text{out}} \simeq L_{\text{in}} e^y$$  \hspace{1cm} (6.2)

It should be noted that for Thomson scattering the mean number of scatterings in the optically thick case is $\tau^2/2$ rather than $\tau^2$. In view of the exponential dependence in eq. 6.2, this is of some importance. It is nonetheless usually disregarded, because $y$ is intended only to indicate whether Comptonization is important ($y \gtrsim 1$) or not. For a detailed discussion on Comptonization, see Rybicki and Lightman (1979, p. 195 ff., principles and qualitative results), Pozdnyakov, Sobol and Sunyaev (1983, many detailed analytical and numerical results), and Sunyaev and Titarchuk (1980, Comptonized continuum spectra of X-ray sources).

6.4.4 Inferred cloud parameters

The best-resembling spectra (no formal model fits were made) have small values of $y$. If $y$ (eq. 6.1) is small, the fractional increase of the energy flux due to Compton up-scattering equals $y$ (eq. 6.2). Due to the limited energy range of the EXOSAT
6.4. Comptonization of burst spectra

ME instrument (1.5-20 keV), the value of $y$ does not equal $y_{\text{obs}} = F_{\text{excess}}/F_{\text{blackbody}}$, because most of the up-scattered photons fall above the upper energy boundary of the EXOSAT window (note that $y$ is a ratio of energy fluxes; it should not be confused with $\epsilon$, which is a ratio of number fluxes). We therefore took a set of model spectra with increasing $y$-values and several combinations of the optical depth and electron temperature, folded them through the EXOSAT detector matrix and fitted them with a blackbody model. The resulting residual number fluxes between 11.7 and 19.8 keV were compared with the residuals of the observed spectra in the same energy range. The fitted blackbody temperatures are slightly higher than the input value used to create the model spectrum. This is to be expected, because the fit procedure will tend to adapt the blackbody temperature to fit the high-energy tail. However, this is of no consequence to the discussion because the same effect will occur in the treatment of the observed spectra.

Fig. 6.1 shows an example of an observed mean spectrum (a), and the simulated spectrum that best resembles this observed spectrum (b). The observed mean spectrum and the simulated spectrum are shown as crosses in the top panels of Fig. 6.1a and b, respectively. The best blackbody fits on these spectra are represented by the dashed lines. The lower panels show the fit residuals.

The model spectra which give the best-resembling fit residuals have $y$ in the range $0.15 - 0.2$. No good values of $\tau$ and $kT_e$ separately could be deduced, both because of the rather limited statistics in the observed spectra, and because the spectral characteristics required to separate these parameters mainly lie outside the spectral range accessible with EXOSAT.

For the formal best-fit excess, comparison with simulations shows that $kT_e$ must exceed 60 keV, implying (eq. 6.1) that $\tau$ is less than 0.5. If we allow for the systematic calibration uncertainty, an extra excess between $-1.5\%$ and $+1.5\%$ may exist in addition to the formal fit excess of $0.5\%$. This means that the true value of $y$ can be anything between 0 and 0.5. Since both calibration effects introduce an excess that is similar at all photon energies between 10 and 20 keV, we conclude that the spectrum of the true excess (if there is any) is approximately flat, like that of the apparent one (Fig. 6.1). This means that the lower limit on $kT_e$ that we inferred from the apparent excess will also be roughly correct for the true excess. We may then combine that limit (60 keV) with the one on $y$ to infer an upper limit of about 1 on $\tau$. Since the $y$-limits include the case of no cloud at all, i.e. $\tau=0$, no meaningful overall bound on the electron temperature can be set. In summary, the following limits can be set to Comptonization parameters during bursts:

- $\tau \leq 1$
- $y \leq 0.5$

These limits apply to burst spectra with luminosities up to at least $0.8 L_E$. For the most luminous ones, radius expansion occurs and the temperature rapidly varies with time (see e.g. Tawara et al. 1984 Lewin, Va\'cca and Basinska 1984). Because the means of those spectra include contributions from many different blackbody temperatures, we cannot be definite about the meaning of an excess in these spectra (note that also in these spectra the 2% upper limit is not violated).
6.5 Analysis of the persistent emission

6.5.1 The observations

The constraints on the parameters of the Comptonizing cloud in burst spectra, derived in the previous Section, can be compared with the parameters inferred from the persistent spectra. The persistent emission was divided in intervals of about 1000 s, excluding the data of 5 May 1984, during which the background varied considerably, and avoiding the bursts. We selected 80 intervals, covering the entire range of observed levels of persistent emission. From these intervals a spectrum was accumulated and fitted with a model of the form $f(E) = CE^{-\Gamma}e^{-E/E_c}$, which is often used as an approximation to the Sunyaev-Titarchuk model in the case of unsaturated Comptonization ($y \lesssim 1$, see Rybicki and Lightman 1979, and Section 6.5.2). In these fits we included a correction for interstellar absorption, with a variable value for the equivalent hydrogen column density $N_H$. Fig. 6.2 shows the fitted power law index, $\Gamma$, and the cut off energy, $E_c$, as a function of the persistent flux level. There is a global trend of $\Gamma$ with persistent flux. At low persistent fluxes ($\lesssim 2 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$), $\Gamma \sim 1.8$, while at high persistent fluxes ($\gtrsim 2.5 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$), $\Gamma \sim 1.3$. The cut off energy behaves somewhat more irregularly. About 20% of the fits result in cut off energies $> 30$ keV, which is too high to give reliable results within the EXOSAT energy window, resulting in large errors in the cut off energies. These data points are distributed evenly over the persistent flux range, except at the highest fluxes ($\gtrsim 2.5 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$) where all fits yield low cut off values. Fig. 6.2c shows that the two parameters $\Gamma$ and $E_c$ are strongly correlated. Therefore, these results should be regarded with some care (see also the next Section). Our results are consistent with previous analyses (that used a much smaller data set) of the persistent emission of 1636-53 by Vacca et al. (1987) and White, Stella and Parmar (1988, see note (i) below eq. 6.7 for a proper comparison with their results). We find values for $\Gamma$ and $E_c$ which are slightly lower than those found by Breedon et al. (1986). We confirm the positive correlation they found between $\Gamma$ and persistent flux level for the data collected in 1983. This leads to the surprising conclusion that although the overall trend for $\Gamma$ is to decrease with persistent flux, there may be periods in time where $\Gamma$ is increasing with persistent flux level.

This inversion of a global trend of spectral hardness versus source intensity during short periods of time has also been seen by Mitsuda et al. (1989) in 1608-52. To see how the source spectral state of 1608-52 in their data compares with our data on 1636-53, we show (Fig. 6.3a) a hardness-intensity diagram (i.e. a diagram of a ratio of count rates in two passbands versus the count rate in another passband) of 1636-53 using the same hardness ratio as that in Mitsuda et al.'s figure 1 (similar hardness-intensity diagrams of this source have been published by Schulz et al. 1989). If we scale the count rates of 1636-53 to what they would be if 1636-53 were at the same distance as 1608-52 by assuming that the respective values of their Eddington fluxes (from radius expansion bursts) correspond to the same luminosity (the Eddington flux of 1608-52 is $17.4 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, Nakamura et al. 1989) we obtain the schematic hardness-intensity diagram of Fig. 6.3b. The highest count rates in our observations correspond approximately to the lowest count rates in the 1983 data of
6.5. Analysis of the persistent emission

![Graph A](image1)

**Figure 6.2** Results of the fits to the persistent emission. (a) The best-fit value of the (photon) spectral index $\Gamma$ versus the persistent flux (5–15 keV). The 1983 data are marked with open squares. The trend in this subset, especially at the lower persistent fluxes, is seen to be opposite to the general decrease of $\Gamma$ with persistent flux. (b) As (a), for the best-fit value of the cut off energy $E_c$. The 1983 data have not been marked. Fit values above 50 keV were omitted (these have very large errors) here and in (c). (c) Cut-off energy versus best-fit spectral index. Errors have been omitted for clarity; the errors on the individual points are consistent with no intrinsic spread of the points around the mean correlation.
Figure 6.3 (a) Hardness-Intensity diagram of 1636–53. The X-ray colour along the abcissa is the ratio of the 6–10 keV count rate to the 2–6 keV count rate. The ordinate is the 2–20 keV count rate (all uncorrected for interstellar absorption). Crosses depict data from the 1983 observation. (b) Schematic Hardness-Intensity diagram in which both the TENMA data of 1608–52 and the EXOSAT data of 1636–53 are depicted. It is seen that the data on 1636–53 are in an intensity range for which there are no data on 1608–52. The abcissa scale shows relative intensities only, the position of one data set relative to the other being fixed by assuming that the Eddington fluxes of both sources correspond to the same luminosity. The diagram should be treated with care, because the differing detector characteristics of the two instruments are not accounted for.
6.5. Analysis of the persistent emission

1608–52, but the hardness ratio at this point is smaller in 1636–53. We emphasize that a detailed comparison of the two observations is not possible, due to the difference in instrumental properties between TENMA and EXOSAT. We note that the fits by Mitsuda et al. to their 1983 data using an unsaturated Comptonization plus blackbody model (their model 2) yield values of $\Gamma$ and $kT_e$ consistent with our values at the same approximate count rates. There are no data for 1636–53 that correspond to the low-intensity data of 1608–52; we point out the peculiar position in Fig. 6.3a of the 1983 observations; it seems that 1636–53 was in some peculiar state at that time. Recent results by Hasinger and Van der Klis (1989) show that this is an ‘island’-state, that is characterized by a broad noise component up to ~ 100 Hz in the power spectrum, and defines a piece of the ‘atoll’.

6.5.2 Choosing a model for the persistent emission

It is a matter of dispute how much of the persistent emission is contributed by a hot cloud surrounding the neutron star, by a boundary layer between the neutron star and the disk or by the disk. This has led various authors to adopt different spectral models of the persistent emission, inspired by their opinion on the nature of the emission region (see e.g. Mitsuda et al. 1984, White, Peacock and Taylor 1985). We shall try to estimate the approximate physical conditions in the inner flow in low-luminosity sources in order to see which simple spectral model is consistent with such estimates.

The Eddington flux of the source is known (Section 6.2) to be $(65 \pm 5) \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$. The luminosity of the persistent emission is then $0.02 - 0.055$ times the Eddington luminosity $L_E$ (assuming the source is always an isotropic emitter; see Van Paradijs, Penninx and Lewin 1988 for extensive results on Eddington limits of burst sources). At these low luminosities, the highest effective temperatures reached are about 0.8 keV on the neutron star surface and also about 0.8 keV in the disk if it extends down almost to the surface (or only 0.2 keV if it is interrupted at the Alfvén radius, see below). The fact that spectra have radiation temperatures much higher than this indicates that non-thermal emission mechanisms and/or scattering dominate the inner regions. As discussed in Section 6.3, X-ray burst spectra strongly resemble Planck functions in spite of the dominance of scattering opacity over absorption opacity, be it at a colour temperature up to 1.6 times the effective temperature (London, Taam and Howard 1986). This has led Mitsuda et al. (1989) to assume that disks at low accretion rates can still look like multi-temperature blackbodies. If $\alpha$-disks are viable models for accretion disks this is most likely incorrect. We shall demonstrate this by computing some features of the inner disk using the equations of Shakura and Sunyaev (1973) for the structure of $\alpha$-disks. Firstly, we have the effective absorption optical depth $\tau_* = \sqrt{\tau T_{\text{eff}}}$, with $\tau_{\text{ff}}$ the free-free optical depth:

$$\tau_* = 8.4 \times 10^{-5} \alpha^{-17/16} l^{-2} m^{-1/16} r^{-93/32} (1 - r^{-1/2})^{-2}$$

(6.3)

Here $l = L/L_E$, $m = M/M_\odot$, and $r = R/3R_S$ with $R_S$ the neutron star Schwarzschild radius. In the following we assume the neutron star mass to be $1.4 M_\odot$ and its radius to be 10 km. The above formula is valid in the inner regime, where radiation pressure dominates gas pressure and electron scattering opacity dominates free-free opacity.
The dimensionless outer radius $r_{\text{out}}$ of this regime of pressure and opacity is given by the relation

$$r_{\text{out}}(1 - r_{\text{out}}^{-1/2})^{-16/21} = 150\alpha^{2/21}16^{21}$$

(6.4)

In addition, the disk may not extend inwards all the way to the neutron star because it is disrupted by the magnetic field of the latter. The radius at which this disruption sets in is somewhat difficult to estimate, both because the interaction between field and flow is ill-understood and because only indirect evidence exists about the strength of the magnetic field of old neutron stars. We shall estimate the inner disk radius to lie where magnetic stresses begin to dominate matter stresses, which is roughly at the so-called Alfvén radius $R_A$:

$$r_A \equiv \frac{R_A}{3\mathcal{R}_S} \simeq 2.8B_9^{4/7}1^{-2/7},$$

(6.5)

where $B_9$ is the surface field strength in units of $10^9$ G. Inside $R_A$, magnetic stresses are usually assumed to quickly direct the matter to the stellar surface, thus keeping the column density and emission of radiation at a very low level (see Ghosh and Lamb 1979a,b, and Spruit and Taam 1989, and references therein for a discussion of the interaction between the inner disk and the neutron star magnetic field). A field of $10^8-10^9$G is often inferred (e.g. Alpar and Shaham 1985, Van den Heuvel, Van Paradis and Taam 1986, Kulkarni 1986). If we set $B_9 = 1$ in eq. 6.5 we find dimensionless inner disk radii of 6-9 for $l = 0.02 - 0.055$. The outer radius of the radiation dominated part of the disk is 5-14, nearly independent of the viscosity parameter $\alpha$.

For the above parameter ranges, the maximum effective optical depth reached in the inner disk is $(3 - 9) \times 10^{-4}\alpha^{-17/16}$. This implies that we do not expect a spectral shape that is locally blackbody-like unless $\alpha$ is less than $10^{-3}$ (most estimates set it at 0.1–1). In the atmospheres of bursting neutron stars, the situation is quite different: $\tau_*$ is nearly infinite and the spectrum is that of a blackbody at large effective optical depths, whereas none of that holds for the disk. We therefore do not think that the justification given by Mitsuda et al. (1989) for their assumption that the disk emits a spectrum that is locally (i.e. at each distance from the neutron star) Planckian, is valid. We shall therefore adopt another extreme viewpoint in terms of spectral shape, which is that the inner disk with its small effective optical depth can only create few ‘seed’ photons that have to gain energy by inelastic scattering on electrons (Comptonization) in order to enable the disk to radiate away the heat it gains by conversion of gravitational potential energy.

We must note here that both this model and that by Mitsuda et al. suffer from a fundamental lack of consistency: one first adopts an approximate model for the structure of the accretion flow (namely, the $\alpha$-model) and then tries to ‘compute’ an emergent spectrum as if that could be done independently in a radiation-dominated environment. Recently, work by White and Lightman (1989), that takes better account of radiation in the equations for the flow structure, has shown that the conditions in the disk around a radius of 2 neutron star radii are such that the electron temperature rises to values near $mc^2/k$ even at luminosities less than $0.1L_E$. This means pair production becomes important before the disk reaches an equilibrium in which it radiates all released binding energy. Since spectra of low-luminosity burst sources do not emit predominantly at energies of 1 MeV (i.e. the intensity decreases
towards higher photon energies in the 2–20 keV range), this may indicate that the inner disk is indeed not present in these sources, i.e. disrupted by the magnetic field. On these grounds, we shall here assume the electron temperature in the relevant region to be much lower than $mc^2/k$.

We note that the absence of the innermost part of the disk, combined with the fact that the remaining part of the disk is geometrically thin, implies that there is no matter in our line of sight to the neutron star surface. Yet we see no pulses at millisecond periods (upper limit 15% in 1636–53, Mereghetti and Grindlay 1987), and it has often been argued that neutron stars with fields of $10^9$ G should give rise to observable pulsations at the neutron star rotation frequency. Recently, however, Asaoka and Hoshi (1989) have shown that these pulsations may have amplitudes as low as 3% (for the most favourable viewing angles) due to the large opening angle of the polar caps. We therefore believe that the non-detection of pulses in 1636–53 and similar sources is quite compatible with the absence of material in our line of sight to the neutron star. This removes some observational support for the hypothesis of Hasinger and Van der Klis (1989), that ‘atoll’-sources differ from ‘Z’-sources because the magnetic fields of ‘atoll’-sources are much weaker.

The photon number spectrum emerging from such an environment has been computed by Sunyaev and Titarchuk (1980):

$$n_\nu = C \nu^2 e^{-\frac{\hbar \nu}{k T_e}} \int_0^\infty t^{\Gamma-2} e^{-t} \left(1 + \frac{k T_e}{\hbar \nu} t\right)^{\Gamma+4} dt$$

(6.6)

Here, $T_e$ is the electron temperature, assumed to be the same in the whole layer, and $\Gamma$ is (for a disk geometry)

$$\Gamma = \frac{1}{2} + \sqrt{\frac{9}{4} + \frac{\pi^2}{12} \frac{mc^2}{(\tau + \frac{3}{2})^2 k T_e}},$$

(6.7)

in which $\tau$ is the Thomson optical depth from the disk midplane to its surface; it should exceed about 3 for eq. 6.6 to be valid. Note (i) that the numerical factor $\pi^2/12$ under the root in (6.7) is $\pi^2/3$ for a spherical geometry; authors who assume a spherical geometry therefore quote $\tau$-values that are about twice as high for the same $\Gamma$ and (ii) that most theoretical papers use the spectral index of the intensity $\alpha \equiv \Gamma - 1$ rather than $\Gamma$; we also quote values of $\alpha$ in our figures and tables. Both $k T_e$ and $\hbar \nu$ should be much less than the electron rest energy for this approximation to the spectral shape to be valid. This spectral shape is not often used in fits to observed spectra because it requires a cumbersome numerical integration for each frequency value at each iteration step in a nonlinear fit procedure (for exceptions, see e.g. Hasinger et al. 1986 and White, Stella and Parmar 1988). This is especially problematic when many spectra have to fitted, like in our case. Asymptotic approximations to (6.6) are

$$n_\nu = A \nu^{-\Gamma} \quad \hbar \nu \ll k T_e$$

(6.8)

$$n_\nu = B \nu^2 e^{-\frac{\hbar \nu}{k T_e}} \hbar \nu \gg k T_e$$

(6.9)

Many authors have proposed a combination of the asymptotics, namely

$$n_E = C E^{-\Gamma} e^{-\frac{E}{k T_e}}$$

(6.10)
to be a valid approximation to (6.6). This simple spectral shape has found wide application in fitting spectra of low-luminosity X-ray sources, but it is valid with some accuracy only for \( y \ll 1 \), or (eq. 6.7) \( \Gamma \gg 2 \). It is not valid for the spectra we observed from 1636–53, since (i) we measure smaller values of \( \Gamma \) and (ii) the transition region, \( E \sim kT_e \), between the asymptotic expressions is in the observed energy range. Since both (i) and (ii) hold for most EXOSAT observations of the persistent spectra of burst sources, we feel that the approximation (6.10) is generally unsuitable for directly deriving physical parameters of these sources.

### 6.5.3 Derivation of the physical parameters of the emitting region

In order to derive the physical parameters \( \tau \) and \( kT_e \) from the observed \( \Gamma_{obs} \) and \( E_c \), we must therefore establish a relationship between the two sets of parameters. Since the observed parameters are the outcome of a fit procedure, this relationship will depend on the range of photon energies accessible with the instrument used, the source and background count rates and (because the spectra steeply increase towards lower photon energies) the magnitude of the interstellar absorption. We therefore adopted the following procedure: for each value of \( \Gamma \) and \( kT_e \) of a source emitting exactly according to eq. 6.6, we computed the spectral shape, normalized it to have a total count rate equal to that received from 1636–53, added an interstellar absorption and binned it into the EXOSAT energy grid. We then computed errors on the number of counts per bin that would apply if a spectrum of that shape and count rate were observed by EXOSAT with a similar background as in our observations of 1636–53. To estimate realistic errors on the fit parameters we made 'synthetic observations' of the ideal Sunyaev-Titarchuk emitters by drawing random numbers of counts in each energy bin from normal distributions with means and spreads equal to the numbers of counts and errors computed for these ideal spectra. These were then fitted by the simple model (6.10), including a free parameter \( N_H \) describing the interstellar absorption. This drawing and fitting was repeated 145 times per parameter set \((\Gamma, kT_e, N_H)\) for a range of values of \( \Gamma \) and \( kT_e \) and two values of \( N_H \): the canonical one of \( 56 \times 10^{20} \) \( \text{cm}^{-2} \) and 0 for comparison. The mean and spread of the fit parameters, and the correlations between them, were recorded. The principle outcome – the mean values of \( \Gamma_{fit} \) and \( E_c \) – are shown as contour plots for both values of \( N_H \) in Fig. 6.4a–b. It is seen that the outcome depends rather strongly on \( N_H \). It is therefore difficult to derive physical cloud parameters in this manner without prior knowledge of the value of \( N_H \), and taking into account the precise energy grid used in the observations. Our contour plots should therefore not be used as conversion tools for other observations.

We next computed weighted means of subsequent sets of 8 points in the plots of \( \Gamma_{obs} \) and \( E_c \) versus persistent emission (see Fig. 6.2), and converted these mean values to values of \( \tau \), \( kT_e \) and \( y \) with the help of Fig. 6.4 (the values of means of observed and derived quantities are listed in Table 6.3). Panels a–d of Fig. 6.5 show the correlations of \( \tau \), \( kT_e \) and \( y \) with persistent emission and of \( \tau \) with \( kT_e \), respectively, for \( N_H = 56 \times 10^{20} \) \( \text{cm}^{-2} \). Fig. 6.6 shows the same correlations for \( N_H = 0 \). It is seen that the values of \( y \) and \( \tau \) are somewhat larger, and of \( kT_e \) somewhat smaller for \( N_H = 0 \) than for \( N_H = 56 \times 10^{20} \) \( \text{cm}^{-2} \).

In order to find out whether any of the correlations are significant, we fitted
6.5. Analysis of the persistent emission

Figure 6.4 Conversion of fitted parameters ($\Gamma_{obs}$, $E_c$) to physical parameters ($kT_e, \alpha$). Contours of equal $\Gamma_{obs}$ (full lines) and contours of equal $E_c$ (dashed lines) are drawn in the ($kT_e, \alpha$)-plane. The noisy character of some contours is due to the limited number (145) of simulations per pair of ($kT_e, \alpha$)-values used to obtain the mean values of $\Gamma_{obs}$ and $E_c$ (see text). The values of $kT_e$ for which simulations were done are 2-8 keV in steps of 0.5 keV and those of $\alpha$ are 0.5-1.3 in steps of 0.05. (a) Results for $N_H = 0.56 \times 10^{22}$ cm$^{-2}$. Contour values of $\Gamma$ range from 0.2 (lower left) to 2.2 (upper right) in equal steps of 0.2. Contour values of $E_c$ are (from left to lower right) 4, 6, 8, 10, 15, 20, 25, 30, 40, 60, 80 and 100 keV. (b) Results for $N_H = 0$. Contour values of $\Gamma$ range from 0.6 (lower left) to 2.2 (upper right) in equal steps of 0.2. Contour values of $E_c$ are (from left to lower right) 6, 8, 10, 15, 20, 25, 30, 40, 60, 80, and 100 keV.

Figure 6.4 Conversion of fitted parameters ($\Gamma_{obs}, E_c$) to physical parameters ($kT_e, \alpha$). Contours of equal $\Gamma_{obs}$ (full lines) and contours of equal $E_c$ (dashed lines) are drawn in the ($kT_e, \alpha$)-plane. The noisy character of some contours is due to the limited number (145) of simulations per pair of ($kT_e, \alpha$)-values used to obtain the mean values of $\Gamma_{obs}$ and $E_c$ (see text). The values of $kT_e$ for which simulations were done are 2-8 keV in steps of 0.5 keV and those of $\alpha$ are 0.5-1.3 in steps of 0.05. (a) Results for $N_H = 0.56 \times 10^{22}$ cm$^{-2}$. Contour values of $\Gamma$ range from 0.2 (lower left) to 2.2 (upper right) in equal steps of 0.2. Contour values of $E_c$ are (from left to lower right) 4, 6, 8, 10, 15, 20, 25, 30, 40, 60, 80 and 100 keV. (b) Results for $N_H = 0$. Contour values of $\Gamma$ range from 0.6 (lower left) to 2.2 (upper right) in equal steps of 0.2. Contour values of $E_c$ are (from left to lower right) 6, 8, 10, 15, 20, 25, 30, 40, 60, 80, and 100 keV.

straight lines to the data in all plots, taking into account the errors in both abscissa and ordinate values. Table 6.4 lists the best value of the slope of the fitted line and its formal standard deviation for all relations plotted in Fig. 6.5 and 6.6. It also lists the probability that a random slope drawn from a normal distribution with the mean and deviation derived from the fit should lie outside the quadrant in which the mean value lies. We take this probability to be a measure for the probability that the slope is consistent with being horizontal or vertical (i.e. that the variables plotted are uncorrelated). These probabilities imply that $\tau$ significantly decreases with increasing electron temperature, and that $y$ and $\tau$ increase quite significantly with increasing
Table 6.3 Results of the fits to the persistent spectra

<table>
<thead>
<tr>
<th>persistent flux ((10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}))</th>
<th>(\Gamma)</th>
<th>(E_c) (keV)</th>
<th>(kT_e) (keV)</th>
<th>(\alpha)</th>
<th>(\tau_T)</th>
<th>(y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.26 ± 0.05</td>
<td>1.88 ± 0.08</td>
<td>21 ± 10</td>
<td>4.7^{+1.0}_{-1.2}</td>
<td>1.07^{+0.04}_{-0.02}</td>
<td>3.9^{+0.6}_{-0.5}</td>
<td>0.55^{+0.03}_{-0.02}</td>
</tr>
<tr>
<td>1.65 ± 0.03</td>
<td>1.49 ± 0.21</td>
<td>6.8 ± 1.8</td>
<td>2.7^{+0.6}_{-0.5}</td>
<td>1.06^{+0.03}_{-0.03}</td>
<td>5.4^{+0.5}_{-0.7}</td>
<td>0.61^{+0.02}_{-0.02}</td>
</tr>
<tr>
<td>1.74 ± 0.03</td>
<td>1.52 ± 0.13</td>
<td>7.4 ± 0.9</td>
<td>2.9^{+0.3}_{-0.4}</td>
<td>1.05^{+0.02}_{-0.03}</td>
<td>5.2^{+0.4}_{-0.3}</td>
<td>0.61^{+0.02}_{-0.02}</td>
</tr>
<tr>
<td>1.81 ± 0.02</td>
<td>1.61 ± 0.20</td>
<td>14.1 ± 3.0</td>
<td>4.1^{+0.8}_{-0.7}</td>
<td>0.96^{+0.06}_{-0.04}</td>
<td>4.6^{+0.4}_{-0.6}</td>
<td>0.66^{+0.04}_{-0.06}</td>
</tr>
<tr>
<td>1.90 ± 0.06</td>
<td>1.59 ± 0.06</td>
<td>14.2 ± 2.6</td>
<td>4.1^{+0.2}_{-0.4}</td>
<td>0.94^{+0.02}_{-0.01}</td>
<td>4.6^{+0.3}_{-0.1}</td>
<td>0.68^{+0.01}_{-0.01}</td>
</tr>
<tr>
<td>2.13 ± 0.04</td>
<td>1.62 ± 0.07</td>
<td>10.1 ± 1.3</td>
<td>3.4^{+0.2}_{-0.3}</td>
<td>1.04^{+0.04}_{-0.02}</td>
<td>4.8^{+0.2}_{-0.1}</td>
<td>0.60^{+0.01}_{-0.01}</td>
</tr>
<tr>
<td>2.28 ± 0.05</td>
<td>1.56 ± 0.34</td>
<td>7.8 ± 3.3</td>
<td>3.0^{+1.1}_{-0.8}</td>
<td>1.06^{+0.09}_{-0.04}</td>
<td>5.1^{+0.8}_{-1.1}</td>
<td>0.60^{+0.04}_{-0.07}</td>
</tr>
<tr>
<td>2.48 ± 0.07</td>
<td>1.81 ± 0.07</td>
<td>19.1 ± 9.5</td>
<td>4.6^{+0.8}_{-1.2}</td>
<td>1.04^{+0.03}_{-0.02}</td>
<td>4.0^{+0.6}_{-0.4}</td>
<td>0.58^{+0.03}_{-0.02}</td>
</tr>
<tr>
<td>2.66 ± 0.05</td>
<td>1.41 ± 0.17</td>
<td>7.2 ± 1.6</td>
<td>2.9^{+0.5}_{-0.5}</td>
<td>0.99^{+0.02}_{-0.02}</td>
<td>5.4^{+0.5}_{-0.5}</td>
<td>0.66^{+0.02}_{-0.02}</td>
</tr>
<tr>
<td>2.98 ± 0.06</td>
<td>1.11 ± 0.11</td>
<td>7.0 ± 0.3</td>
<td>3.0^{+0.4}_{-0.3}</td>
<td>0.82^{+0.02}_{-0.02}</td>
<td>6.0^{+0.3}_{-0.4}</td>
<td>0.86^{+0.02}_{-0.02}</td>
</tr>
</tbody>
</table>

Some correlations, especially that between \(y\) and the persistent flux, need a somewhat more careful approach: the line fits indicate that the rising trend of \(y\) with increasing flux is very significant, but the scatter of the data around the best fit is much larger than the errors in the data. The scatter must therefore be intrinsic to the source, and because the total observation time devoted to these spectra is much smaller than the total time difference between the first and last observation, it is quite possible that we have just sampled a few points of a (possibly correlated) random walk of the source properties in the \(y\) versus flux plane. As a second test, we therefore computed the linear correlation coefficients of all relations; these are listed in Table 6.4 as well, together with the probability that a random sample of 10 points drawn from an uncorrelated bivariate distribution should have an absolute value of the correlation coefficient that is greater than the absolute value of the computed correlation coefficient of the relation under consideration. It is seen that this second measure of the significance of the relation is usually more pessimistic about the existence of a correlation, especially for the case of \(y\) versus persistent flux. As a measure of the significance of each correlation, we shall adopt the more pessimistic of the two probabilities listed in Table 6.4. As discussed in Section 6.5.1, the fit parameters \(\Gamma\) and \(E_c\) are strongly correlated; part of this correlation may be an artefact of the fit procedure. As a result, the correlation between \(\tau\) and \(kT_e\) (both functions of \(\Gamma\) and \(E_c\)) may be artificially strengthened. The other correlations are not affected by this.

We may therefore state that the scattering optical depth \(\tau\) and the Compton
Comparison of the results for burst and persistent spectra

6.6. Comparison of the results for burst and persistent spectra

6.6.6. Comparison of the results for burst and persistent spectra

Table 6.3 (continued) Results of the fits to the persistent spectra

<table>
<thead>
<tr>
<th>pers. flux (10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1})</th>
<th>\Gamma</th>
<th>E_c (\text{keV})</th>
<th>kT_e (\text{keV})</th>
<th>\alpha</th>
<th>\tau_T</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.26 \pm 0.05</td>
<td>1.88 \pm 0.08</td>
<td>21 \pm 10</td>
<td>3.9_{-1.0}^{+0.8}</td>
<td>1.02_{-0.04}^{+0.05}</td>
<td>4.5_{-0.5}^{+0.6}</td>
<td>0.61_{-0.04}^{+0.03}</td>
</tr>
<tr>
<td>1.65 \pm 0.03</td>
<td>1.49 \pm 0.21</td>
<td>6.8 \pm 1.8</td>
<td>2.3_{-0.6}^{+0.8}</td>
<td>0.91_{-0.03}^{+0.04}</td>
<td>6.6_{-1.2}^{+0.9}</td>
<td>0.76_{-0.03}^{+0.03}</td>
</tr>
<tr>
<td>1.74 \pm 0.03</td>
<td>1.52 \pm 0.13</td>
<td>7.4 \pm 0.9</td>
<td>2.4_{-0.4}^{+0.5}</td>
<td>0.91_{-0.02}^{+0.03}</td>
<td>6.4_{-0.7}^{+0.6}</td>
<td>0.76_{-0.03}^{+0.02}</td>
</tr>
<tr>
<td>1.81 \pm 0.02</td>
<td>1.61 \pm 0.20</td>
<td>14.1 \pm 3.0</td>
<td>3.3_{-0.8}^{+0.7}</td>
<td>0.87_{-0.05}^{+0.08}</td>
<td>5.5_{-0.7}^{+0.7}</td>
<td>0.78_{-0.09}^{+0.05}</td>
</tr>
<tr>
<td>1.90 \pm 0.06</td>
<td>1.59 \pm 0.06</td>
<td>14.2 \pm 2.6</td>
<td>3.3_{-0.3}^{+0.3}</td>
<td>0.85_{-0.02}^{+0.02}</td>
<td>5.6_{-0.3}^{+0.3}</td>
<td>0.80_{-0.02}^{+0.02}</td>
</tr>
<tr>
<td>2.13 \pm 0.04</td>
<td>1.62 \pm 0.07</td>
<td>10.1 \pm 1.3</td>
<td>2.8_{-0.3}^{+0.3}</td>
<td>0.93_{-0.03}^{+0.02}</td>
<td>5.7_{-0.3}^{+0.4}</td>
<td>0.72_{-0.02}^{+0.02}</td>
</tr>
<tr>
<td>2.28 \pm 0.05</td>
<td>1.56 \pm 0.34</td>
<td>7.8 \pm 3.3</td>
<td>2.5_{-1.0}^{+1.3}</td>
<td>0.94_{-0.05}^{+0.10}</td>
<td>6.2_{-1.9}^{+1.3}</td>
<td>0.73_{-0.11}^{+0.05}</td>
</tr>
<tr>
<td>2.48 \pm 0.07</td>
<td>1.81 \pm 0.07</td>
<td>19.1 \pm 9.5</td>
<td>3.7_{-1.1}^{+0.7}</td>
<td>0.98_{-0.03}^{+0.03}</td>
<td>4.7_{-0.5}^{+0.8}</td>
<td>0.65_{-0.03}^{+0.03}</td>
</tr>
<tr>
<td>2.66 \pm 0.05</td>
<td>1.41 \pm 0.17</td>
<td>7.2 \pm 1.6</td>
<td>2.4_{-0.4}^{+0.6}</td>
<td>0.85_{-0.02}^{+0.03}</td>
<td>6.7_{-1.0}^{+0.6}</td>
<td>0.83_{-0.04}^{+0.03}</td>
</tr>
<tr>
<td>2.98 \pm 0.06</td>
<td>1.11 \pm 0.11</td>
<td>7.0 \pm 0.3</td>
<td>2.5_{-0.2}^{+0.3}</td>
<td>0.67_{-0.01}^{+0.02}</td>
<td>7.6_{-0.5}^{+0.3}</td>
<td>1.13_{-0.03}^{+0.02}</td>
</tr>
</tbody>
</table>

The y parameter show a moderately significant increase with increasing persistent flux (and therefore with the accretion rate); one does in fact expect the optical depth to increase with increasing mass accretion rate in simple accretion flow models (because the column density of matter in the disk increases with mass accretion rate). The electron temperature rises significantly with decreasing optical depth. Many emission models will indeed display such behaviour if the disk has to provide a substantial luminosity at low optical depths: the smaller the optical depth, the fewer photons are produced and the more energy each photon has to carry. The decreasing trend of the electron temperature with persistent flux is insignificant.

6.6 Comparison of the results for burst and persistent spectra

6.6.1 A large difference between Comptonization parameters

We have found that the shapes of spectra of bursts from 1636–53 are very nearly Planckian. Allowing for calibration uncertainties, we found a firm upper limit to a high-energy excess of about 2%, independent of parameters of the burst or persistent emission. From this, we derived limits on the parameters of a hot, tenuous plasma cloud around the neutron star that may be the cause of such an excess. These are that $\tau \leq 1$, and $y \leq 0.5$. The upper limits are consistent with parameters that were found in bursts of 1608–52 by Nakamura et al.; they do however find significant excesses and
clear correlations of the excess with burst and persistent emission (see Section 6.1).

We have also inferred, within the framework of the Sunyaev-Titarchuk spectral model, a considerable scattering optical depth of about 4–8 for the region from which the persistent emission originates, and an electron temperature of about 2–5 keV, which demonstrates that this region is tenuous and not optically thick in absorption; it could, e.g., be an inner disk or a boundary layer (or both: we shall call it ‘disk’ below for brevity).

It is seen that the Comptonization parameters inferred from the two kinds of spectra are very different. For the electron temperatures, no definite comparison is possible (see Section 6.4.4), because the burst excess is only an upper limit. We shall not discuss the temperature any further. Quite to the contrary, the optical depth difference is very significant, because the vanishing of the burst excess implies the largest possible difference. The optical depth discrepancy will turn out to have consequences for our knowledge of the inner disk.

### 6.6.2 Implications for the structure of the inner flow

We shall now argue that the inner disk is geometrically thin, both during bursts and quiescence. This is most easily seen to hold during bursts: we infer upper limits

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**Figure 6.5** Correlations between pairs of derived physical variables for $N_H = 0.56 \times 10^{22}$ cm$^{-2}$. (a) Thomson scattering optical depth $\tau$ versus persistent flux. (b) Electron temperature $kT_e$ versus persistent flux. (c) Compton $y$ versus persistent flux. (d) $\tau$ versus $kT_e$. 
6.6. Comparison of burst results and persistent results

![Graphs showing correlations between pairs of derived physical variables for $N_H = 0$.](image)

**Figure 6.6** Correlations between pairs of derived physical variables for $N_H = 0$. (a) Thomson scattering optical depth $\tau$ versus persistent flux. (b) Electron temperature $kT_e$ versus persistent flux. (c) Compton $y$ versus persistent flux. (d) $\tau$ versus $kT_e$.

To the optical depth in our line of sight during bursts that fall so far short of those inferred for the disk that the disk cannot intercept the line of sight to us. The fact that burst spectra are always nearly Planckian (Section 6.3) and that spectral shapes of persistent emission are similar in all burst sources (White, Stella and Parmar 1988) shows that this is not a particular property of 1636–53 alone. The absence of burst sources with strongly non-Planckian burst spectra can in fact be used for a tentative estimate of the inner disk opening angle (i.e. the angle between the line of sight just grazing the inner disk and the disk midplane): the fact that severely distorted burst spectra have not been reported for any of the $\sim 19$ burst sources that have been observed with sufficient integration time and spectral resolution implies that the probability of our line of sight crossing the inner disk is at most of order 1/19. This implies an inner disk opening angle of less than 3 degrees. However, the outer disk has an opening angle of some 5 degrees (Milgrom 1978), and its high opacity implies that sources for which the line of sight to us crosses it are not observable to us as X-ray sources at all. This means that we can only infer that the inner disk opening angle is less than that of the outer disk. The inner region of a Shakura-Sunyaev disk has an opening angle equal to $L/L_E$, which corresponds to 1–3 degrees in the observed range of luminosities for 1636–53.

Can the inner flow be geometrically thick in quiescence? There are two ways in
Table 6.4 The significance of the correlation between parameters of the persistent emission

<table>
<thead>
<tr>
<th>$N_H$</th>
<th>relation</th>
<th>slope $a$</th>
<th>$\sigma_a$</th>
<th>$P_{uncor}^1$</th>
<th>$\rho$</th>
<th>$P_{uncor}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.56</td>
<td>$\tau$ vs. pers. flux</td>
<td>0.801</td>
<td>0.279</td>
<td>0.0021</td>
<td>0.63</td>
<td>0.051</td>
</tr>
<tr>
<td></td>
<td>$kT_e$ vs. pers. flux</td>
<td>-0.304</td>
<td>0.290</td>
<td>0.12</td>
<td>-0.33</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>$y$ vs. pers. flux</td>
<td>0.129</td>
<td>0.0158</td>
<td>$3.6 \times 10^{-16}$</td>
<td>0.63</td>
<td>0.051</td>
</tr>
<tr>
<td></td>
<td>$\tau$ vs. $kT_e$</td>
<td>-0.971</td>
<td>0.360</td>
<td>0.0036</td>
<td>-0.82</td>
<td>0.0037</td>
</tr>
<tr>
<td>0.00</td>
<td>$\tau$ vs. pers. flux</td>
<td>1.413</td>
<td>0.349</td>
<td>$3.4 \times 10^{-5}$</td>
<td>0.69</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>$kT_e$ vs. pers. flux</td>
<td>-0.402</td>
<td>0.261</td>
<td>0.062</td>
<td>-0.54</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>$y$ vs. pers. flux</td>
<td>0.238</td>
<td>0.0222</td>
<td>$3.5 \times 10^{-26}$</td>
<td>0.70</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>$\tau$ vs. $kT_e$</td>
<td>-2.283</td>
<td>0.947</td>
<td>0.0082</td>
<td>-0.84</td>
<td>0.0024</td>
</tr>
</tbody>
</table>

$P_{uncor}^1$ is the probability that a random direction, drawn from a normal distribution with mean and deviation equal to the best fit value and its deviation, should lie outside the quadrant in which the mean value lies.

$P_{uncor}^2$ is the probability that a random sample of 10 points (i.e. the same number of points as in our relations) taken from an uncorrected bivariate normal distribution should incidentally yield a correlation co-efficient that is larger in absolute value than the correlation co-efficient computed for the relation under consideration.

which it could be. The first way would be to have nearly spherically symmetric radial infall of matter. Nearly all lines of sight would be intercepted by such a flow without the flow requiring pressure support to maintain its thickness. By assuming all matter to accrete radially, neglecting gas pressure and treating the radiation pressure as an effective gravity on an optically thin flow, we derive a Thomson optical depth of the accretion column (for accretion of matter with cosmic abundances onto a canonical neutron star) of

$$\tau = 2.7 \frac{l}{\sqrt{1-l}},$$

(6.11)

where $l$ is again $L/L_E$. This implies optical depths less than 0.2 for the observed range of $l$, instead of the observed 4–8 during quiescence (because a burst of radiation reduces the flow speed without changing the accretion rate the optical depth during burst should be even greater than the quiescence value of 4–8 in this model). Thus, the first thick-flow scenario does not apply.

The second way of having a geometrically thick flow is a pressure-supported thick disk. This is impossible if the temperature of matter equals the observed electron temperature of 2–5 keV, so the ion temperature must be much greater than the electron temperature (since radiation pressure is also insufficient). The impinging radiation from the burst could then Compton-cool the disk, undermine its pressure support and ensure that it is out of the line of sight during the burst, as it must be to prevent severe distortions of the blackbody spectra of X-ray bursts. If this scenario is correct, the total source flux of photons with energies above 10 keV must vanish
during the decay part of bursts, because then the burst has too low a temperature for it to produce those photons. At the same time, the numerous low-energy photons that it still emits should cool the electrons in the disk to less than 1 keV, thereby ensuring that the inner disk is also unable to produce photons above 10 keV. In the decay part of bursts, where the total count rate of the source is 200 cts\,s^{-1}, the persistent emission above 10 keV is $6.0 \pm 1.5$ cts\,s^{-1}. Since at most about 1\% of the total count rate may appear erroneously above 10 keV (sect. 6.3.2), we set a generous upper limit to this erroneous part of the count rate of 3 cts\,s^{-1}. This implies that the persistent emission is still at least $3.0 \pm 1.5$ cts\,s^{-1}, which is greater than zero with 98\% confidence. As a result, we may conclude that the second thick-flow scenario also does not apply.

Finally we note that we find no hint of an additional blackbody component in the persistent emission, in agreement with observations of burst sources, but unlike what is seen in more luminous sources (White, Stella and Parmar 1988). This means that there is no significant (i.e. less than 10–20\% of the total intensity) blackbody boundary layer emission from the place where the accretion flow hits the neutron star. There are many ways in which this can be qualitatively explained, e.g.

(i) The boundary layer is optically thin. This depends critically on the radial length scale of the boundary flow (i.e. its Reynolds number), which is unknown. Also, if a magnetic field is present, it can influence the flow out to a larger radius, turning essentially the whole magnetosphere into an extended transition region and more easily keeping it optically thin.

(ii) The matter hitting the neutron star is so nearly in corotation that hardly any kinetic energy is dissipated at the boundary, because the neutron star rotates near its break-up rate.

6.7 Conclusion

We have modelled spectra of 4U/MXB 1636–53 observed with EXOSAT both during bursts and persistent emission. Both models include effects of Comptonization, and we find that there is a large difference between the Comptonization parameters of both types of spectra: in burst spectra, we find an upper limit of 1 on the optical depth and of 0.5 on the Compton y parameter. In persistent spectra, the inferred optical depth is 4–8 and the electron temperature is 2–5 keV (y is 0.8–1.1).

From this difference, we have inferred that the inner accretion flow is geometrically thin when the accretion rate is between 0.02 and 0.055 times the critical (i.e. Eddington) accretion rate, and that it remains thin when it is irradiated by a strong burst of radiation from the neutron star with a peak luminosity at least up to 0.8 $L_E$.

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References