Hard X-Ray Emission from Low-Mass X-Ray Binaries

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters

Citation
Barret, D., J. F. Olive, L. Boirin, C. Done, G. K. Skinner, and J. E. Grindlay. 2000. “Hard X-Ray Emission from Low-Mass X-Ray Binaries.” The Astrophysical Journal 533 (1): 329–51. https://doi.org/10.1086/308651.

Citable link
http://nrs.harvard.edu/urn-3:HUL.InstRepos:41399846

Terms of Use
This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA
HARD X-RAY EMISSION FROM LOW-MASS X-RAY BINARIES

D. Barret, J. F. Olive, and L. Birkin

Centre d’Etude Spatiale des Rayonnements, Centre National de la Recherche Scientifique, Université Paul Sabatier, 9 Avenue du Colonel Roche, 31028 Toulouse Cedex 04, F; Didier.Barret@cesr.fr

C. Done
Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK; chris.done@durham.ac.uk

G. K. Skinner
School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK; gks@star.sr.bham.ac.uk

AND

J. E. Grindlay
Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; josh@head-cfa.harvard.edu

Received 1999 July 28; accepted 1999 November 17

ABSTRACT

We report on Rossi X-Ray Timing Explorer observations of four type I X-ray bursters, namely, 1E 1724−3045, GS 1826−238, SLX 1735−269, and KS 1731−260. The first three were in a low state, with 1−200 keV X-ray luminosities in the range ~0.05−0.1L_Edd (L_Edd: Eddington luminosity for a neutron star, L_Edd = 2.5 × 10^{38} ergs s^{-1}), whereas KS 1731−260 was in a high state, with luminosity ~0.35L_Edd. The low-state sources have very similar power spectra, displaying high-frequency noise up to ~200 Hz. For KS 1731−260, its power spectrum is dominated by noise at frequencies ≤20 Hz; in addition a quasi-periodic oscillation at 1200 Hz is detected in a segment of the observation. The 1−200 keV spectra of the low-state sources are all consistent with resulting from thermal Comptonization with an electron temperature (kT_e) around 25−30 keV. For KS 1731−260, the spectrum is also dominated by thermal Comptonization, but with a much lower kT_e ~3 keV and no significant hard X-ray emission. With the exception of GS 1826−238, they each have an underlying soft component, carrying at most ~25% of the total 1−200 keV luminosity. For all sources, we have detected an iron Kα line at 6.4 keV (although it is weak and marginal in 1E 1724−3045). A reflection component is present in the spectra of GS 1826−238 and SLX 1735−269, and for both we find that the reflecting medium subtends only a small solid angle (Ω/2π ~0.15, 0.28). The origin of the line and the reflection component is most likely to be irradiation of the accretion disk by the X-ray source. We suggest a model in which the region of main energy release, where hard X-rays are produced, would be an optically thin boundary layer merged with an advection-dominated accretion flow (ADAF) and would be responsible for the rapid variability observed. The soft component observed probably represents the unscattered emission from an optically thick accretion disk of variable inner radius. When the accretion rate increases, the inner disk radius shrinks and the strength of the reflected component and associated iron line increase. At the same time, the Comptonization region cools off in response to an increased cooling flux from the accretion disk and from the reprocessed/ reflected component, thus leading progressively to a quenching of the hard X-ray emission. If low-state neutron stars (NSs) accrete via ADAFs, the observation of X-ray bursts, indicating that all the accreting matter actually accumulates onto the NS surface, argues against the existence of strong winds from such accretion flows. Finally, we discuss two criteria recently proposed to distinguish between nonquiescent black holes (BHs) and NSs that are not contradicted by existing observations. The first one states that, when thermal Comptonization is responsible for the hard X-ray emission, only BHs have kT_e larger than ~50 keV. However, this criterion is weakened by the fact that there are NSs displaying nonattenuated power laws extending up to at least 200 keV, possibly implying nonthermal Comptonization or thermal Comptonization with kT_e larger than 50 keV. The second criterion stipulates that only BHs are capable of emitting hard X-ray tails with 20−200 keV luminosities ≥1.5 × 10^{37} ergs s^{-1}.

Subject headings: accretion, accretion disks ⎯ black hole physics ⎯ stars: individual (1E 1724−3045, GS 1826−238, SLX 1735−269, KS 1731−260) ⎯ stars: neutron ⎯ X-rays: bursts ⎯ X-rays: stars

1. INTRODUCTION

It is now well established that hard X-ray emission (E ≥30 keV) from X-ray binaries is not exclusively associated with black hole systems (BHs). The major breakthrough came with the SIGMA and BATSE observations, which provided the first unambiguous detections of type I X-ray bursters (hence neutron star systems, NSs) at ~100 keV (Barret & Vedrenne 1994; Tavani & Barret 1997, and references therein). However, because of the moderate sensitivity and low spectral resolution of these instruments and the lack of simultaneous X-ray observations, it was impossible to investigate the conditions under which NSs emit hard X-rays. Similarly, very little could be inferred about the accretion geometry and the relative contribution of the potential emitting regions to the total emission (NS surface, boundary layer, accretion disk, corona). In addition, the hard X-ray data alone were not good enough to discriminate between the thermal and nonthermal models that have been put forward to account for this emission. Finally, if the emission of hard X-rays is indeed common to BHs and NSs,
there may remain some differences either in the shape of the hard tails (position of the energy cutoff; e.g., Tavani & Barret 1997; Churazov et al. 1997) or in the luminosities that can be radiated simultaneously in soft and hard X-rays\(^1\) (Barret, McClintock, & Grindlay 1996; Van Paradijs & Van der Klis 1994; Barret & Vedrenne 1994; Zhang et al. 1996). All these potential differences have yet to be quantified precisely. They can now be addressed through observations performed by the BeppoSAX and the Rossi X-Ray Timing Explorer (RXTE) satellites, the latter combining the Proportional Counter Array (PCA) and the High-Energy X-Ray Timing Experiment (HEXTE) (Bradt, Rothschild, & Swank ). These two instruments offer for the first time the possibility of observing NSs with good sensitivity and excellent timing capabilities simultaneously from \(2\) to \(\sim 150\) keV.

In this paper, we report on the RXTE observations of four type I X-ray bursters; namely 1E 1724–3045, GS 1826–238, SLX 1735–269, and KS 1731–260. All these sources have in common that they have already been detected up to \(\sim 100\) keV at least once (Tavani & Barret 1997). The analysis has been made in a coherent way for all sources to allow a reliable and consistent comparison of their respective properties. The paper is organized as follows. First we review the relevant spectral observations of the four sources and present their long term RXTE All Sky Monitor (ASM) light curves (§ 2). We then describe our data reduction scheme, before presenting the results of our RXTE pointed observations (§ 3). In § 4, we discuss the main features of our timing and spectral results and their implications for our understanding of NS accretion. Finally, we discuss the most recent observational criteria that have been proposed to distinguish nonquiescent BHs and NSs on the basis on their broad band spectral properties.

2. THE SOURCES

First, let us review briefly the previous observations of these four sources. We will emphasize X-ray spectral observations, in particular previous \(N_{\text{H}}\) measurements relevant to the PCA spectral analysis, existing hard X-ray observations, and finally more general information about these sources.

2.1. 1E 1724–3045

1E 1724–3045 is the most extensively studied of the four sources discussed here. It is located in the globular cluster Terzan 2 in the general direction of the Galactic center. Its distance was first estimated to be \(7.7\) kpc (Ortolani, Bica, & Barbuy 1997) and was recently revised to \(6.6\) kpc (Barbuy, Bica, & Ortolani 1998). It is a weakly variable X-ray source, and a persistent, though variable, hard X-ray source (Goldwurm et al. 1993, 1994, 1995). Details about previous X-ray observations can be found in Barret et al. (1999). Broadband spectral observations have already been performed by BeppoSAX (Guainazzi et al. 1998). They showed that the \(100\) keV spectrum could be well fitted by the sum of a soft and a hard Comptonized component. The former could be equally fitted by a single temperature blackbody (BB) of \(kT_{\text{bb}} = 0.6\) keV, \(R_{\text{bb}} = 12\) km or a multicolor disk blackbody (MCD; Mitsuda et al. 1984) with \(kT_{\text{in}} = 1.4\) keV, \(R_{\text{in}}(\cos \theta)^{1/2} = 2.7\) km (at \(10\) kpc, corresponding to \(R_{\text{in}}(\cos \theta)^{1/2} = 2.0\) km at \(6.6\) kpc). The hard Comptonized component was fitted with a COMPTT model (Titarchuk 1994) with an electron temperature of \(\sim 27\) keV, an optical depth \(\sim 3.3\) for a spherical scattering cloud, and a temperature of \(0.6\) keV \((kT_{\text{bb}})\) for the seed photons. The ratio of the bolometric \((0.1–100\) keV) luminosity of the soft component to the total luminosity was \(11\%\) and \(36\%\) for the BB and MCD models, respectively. However, as pointed out by Guainazzi et al. (1998), whereas the radius derived from the BB fit is close to the NS radius, the very small value inferred for \(R_{\text{in}}\)\(^2\) appears unphysical (for any plausible values of the source inclination); hence, the hypothesis that the soft component comes from the boundary layer around the NS might be preferred.

An ASCA observation confirmed the hardness of the source in X-rays and allowed an accurate determination of \(N_{\text{H}}\) toward the source \((\sim 1.2 \times 10^{22}\) H atoms \(\text{cm}^{-2}\)). This value is consistent with that expected from the optical reddening of the cluster (Barret et al. 1999).

2.2. GS 1826–238

When GS 1826–238 was discovered serendipitously by Ginga in 1988, it was first classified as a transient source, and it was further classified as a black hole candidate (BHC) based on its rapid and intense flickering and hard power-law (PL) spectrum in X-rays (Tanaka 1989). The source was later detected by TTM (In’t Zand 1992), ROSAT PSPC (Barret, Motch, & Pietsch 1995), and at hard X-ray energies by OSSE (Strickman et al. 1996). The BH nature of GS 1826–238 was questioned (e.g., Strickman et al. 1996; Barret et al. 1996), but the firm evidence that GS 1826–238 did not contain a BH came with the discovery of type I X-ray bursts (the unmistakable signature of a NS) with the BeppoSAX wild field cameras (WFC; Ubertini et al. 1997).

In the WFC data, the 70 bursts observed over more than \(2.5\) yr of source monitoring exhibit a quasi-periodicity of \(5.76\) hr in their occurrence times (Ubertini et al. 1999). In addition, the so-called \(\alpha\) parameter, which is the ratio between the average persistent X-ray flux to the average flux emitted during X-ray bursts (assuming that both are isotropic) was estimated to be \(\alpha = 4.9 \pm 2.7\) for two of the 70 bursts analyzed by Ubertini et al. (1999). Similarly In’t Zand et al. (1999), using two bursts, observed \(\alpha = 54 \pm 5\) consistent with the pre-

\(^{2}\) The MCD model returns \(kT_{\text{in}}\) and \(R_{\text{in}}(\cos \theta)^{1/2}\) for an assumed distance, which are the color temperature of the inner accretion disk and the projected inner disk radius (note that in the case of a pseudo-Newtonian disk with zero-stress inner boundary conditions around a Schwarzschild BH, the actual inner disk radius is \(2.73^{+1}_{-1}\) times less than the measured \(R_{\text{in}}\); see Gierliński et al. 1999). Correction for spectral hardening must be made to \(kT_{\text{in}}\) and \(R_{\text{in}}\) to account for the fact that the inner disk opacity is dominated by electron scattering. We use a spectral hardening factor \(f = 1.7\), a value consistent with the source luminosity (Shimura & Takahara 1995), and determine the effective temperature \(kT_{\text{eff}} = kT_{\text{in}} / f\), and the effective inner disk radius \(R_{\text{eff}} = f^{-1}R_{\text{in}}\). For 1E 1724–3045, this means that \(kT_{\text{eff}} = 0.82\) keV, \(R_{\text{in}} = 11.4\) km for an assumed inclination angle of \(60°\) (the source is not a dipper, therefore its inclination must be less than \(75°\)). If we further assume that the disk terminates at the last stable orbit, then, as described in Ebisawa et al. (1994), \(R_{\text{in}}\) (the Schwarzschild radius) is related to \(R_{\text{in}}\) as \(3R_{\text{in}} = 9M_{\odot}\) km \(\times 0.2\sin\theta_{\text{eff}}\) [\(M_{\odot}\) is the mass of the neutron star in units of \(M_{\odot}\), \(\eta < 1\) accounts for the decrease of \(R_{\text{in}}(\cos \theta)^{1/2}\) by relativistic effects [see Ebisawa et al. 1994], and here we take \(\eta = 0.6\) as in Shimura & Takahara 1995]. From this, the low inferred value of \(R_{\text{in}}\) implies a very low mass of \(0.4\) \(M_{\odot}\) for the NS (for a \(1.4\) \(M_{\odot}\) NS, \(R_{\text{in}}\) should be \(37\) km, equivalent to \(R_{\text{in}} = 13\) km). This does not seem to favor the MCD model used to fit the soft component in the BeppoSAX data of 1E 1724–3045. However, one has to keep in mind that \(R_{\text{in}}\) is derived from the normalization of the MCD model and therefore would be underestimated if some fraction of the disk flux is scattered in a corona. The measured value of \(R_{\text{in}}\) derived from the unscattered fraction would then depend on the geometry, and the optical depth of the scattering corona.

\(^1\) In this paper, we define soft X-ray as photons with energy between \(1\) and \(20\) keV (also X-rays) and hard X-rays as photons with energy between \(20\) and \(200\) keV.
vious estimate. This value is consistent with a picture in which all the accreting material is accumulated onto the NS and helium is burned during the bursts ($\alpha$ should be $\sim 20$ and $\sim 80$ for pure hydrogen and helium burning, respectively).

As is the case for 1E 1724$-$3045, broadband observations of GS 1826$-$238 already exist. First, Strickman et al. (1996), combining nonsimultaneous Ginga (X-ray) and OSSE (hard X-ray) data showed that the 2–200 keV spectrum of the source could be fitted by an exponentially cutoff power law (CPL: $\Gamma = 1.76 \pm 0.02$, $E_{\text{cutoff}} = 58 \pm 5$ keV, $\Gamma$ is the photon index of the power law; i.e., the energy index would be $\Gamma - 2$) with a weak (and marginally significant) reflection component. More recently, BeppoSAX observed the source, following a BATSE trigger, which indicated that GS 1826$-$238 was emitting hard X-rays (Frontera et al. 1998; Del Sordo et al. 2000). The 0.5–200 keV spectrum was well fitted by a composite model consisting of a blackbody of $0.94 \pm 0.05$ keV, and a PL of photon index $\Gamma = 1.34 \pm 0.04$, exponentially cutoff at 49 $\pm 3$ keV. The column density measured by BeppoSAX was $0.47 \times 10^{22}$ H atoms cm$^{-2}$, consistent with the ROSAT PSPC value ($0.5 \pm 0.04) \times 10^{22}$ H atoms cm$^{-2}$; Barret et al. 1995), both being slightly larger than the value expected from the optical reddening toward the source [$E(B-V) = 0.4$ corresponding to $0.22 \times 10^{22}$ H atoms cm$^{-2}$; Predehl & Smith 1995; Barret et al. 1995). Another BeppoSAX observation performed 6 months before by In't Zand et al. (1999) yielded best-fit spectral parameters consistent with those reported in Del Sordo et al. (2000).

GS 1826$-$238 has a $V = 19.1 \pm 0.1$ optical counterpart (Barret et al. 1995; Homer, Charles, & O'Donoghue 1998) in a possible 2.1 hr orbital period system and is therefore a low-mass X-ray binary (LMXB). If the 2.1 hr modulation is the true orbital period of the system, one can try to estimate the source distance following the approach of Van Paradijs & McClintock (1994). In LMXBs, the bulk of the optical light originates from the reprocessing of the X-rays in the accretion disk. For systems for which reliable distance estimate exists, there is a good correlation between the absolute $V$ magnitude and the X-ray luminosity ($L_X$) and the size of the accretion disk (and hence the orbital period $P_{\text{orb}} L_X \propto L_X^{1/2} P_{\text{orb}}^{2/5}$). Most LMXBs have $M_V$ in the range 0–2, whereas some short-period systems have $M_V$ in the range 3–5. With a 2.1 hr orbital period, GS 1826$-$238 is a short period system, and if one assumes $M_V$ in the above range (and an absolute dereddened $V$ magnitude of 17.9), one gets a formal distance range between 4 and $\sim 10$ kpc. Constraints on the source distance can also be inferred from the observation of X-ray bursts. In't Zand et al. (1999) derived an unabsorbed bolometric peak flux of a burst of $(2.7 \pm 0.5) \times 10^{-8}$ ergs s$^{-1}$ cm$^{-2}$. The fact that this burst did not show evidence for photospheric expansion implies that its luminosity is below the Eddington limit ($L_{\text{Edd}}$), which we assume to be $2.5 \times 10^{38}$ ergs s$^{-1}$ (this value is appropriate for helium-rich material, a 1.4 $M_\odot$ NS, and a moderate gravitational redshift correction; Van Paradijs & McClintock 1994). This in turn implies an upper limit on the source distance of 9.6 kpc. In the remainder of this paper, we assume a distance of 7 kpc for GS 1826$-$238.

2.3. SLX 1735$-$269

SLX 1735$-$269 was reported for the first time in 1985, when it was detected by the Spacelab 2 X-ray telescope (Skinner et al. 1987). However, it was present in the Einstein Slew Survey in observations performed $\sim 5$ yr earlier (Elvis et al. 1992). SLX 1735$-$269 was later detected by TTM (In't Zand 1992), by ART-P, ROSAT PSPC (Grebeznev, Pavlinsky, & Sunyaev 1996), and ASCA (David et al. 1997). SIGMA observations have shown that it is a persistent hard X-ray source of the Galactic center region (Goldwurm et al. 1996). The weakness of the source ($\sim 15.4$ mcrab in the 35–75 keV range) did not allow tight constraints to be put on the time-averaged (1990–1994) hard X-ray spectrum, which could be fitted either by a simple PL of photon index $\Gamma \sim 2.9 \pm 0.3$, or alternatively by a Comptonization model (COMPST in XSPEC; Sunyaev & Titarchuk 1980) with $kT_e$ of $26.3^{+3}_{-2}$ keV (Goldwurm et al. 1996). Although early suspected to contain a NS based on the softness of its hard X-ray spectrum (Goldwurm et al. 1996), its nature remained uncertain until type I X-ray bursts were discovered with the BeppoSAX WFC (Bazzano et al. 1997a). The ASCA observations of SLX 1735$-$269 revealed that its 0.6–10 keV spectrum could be well fitted with a PL of index 2.15 (David et al. 1997), absorbed through an $N_H$ of $(1.4–1.5) \times 10^{22}$ H atoms cm$^{-2}$, a value that is consistent with a source location near the Galactic center (i.e., at a distance of $\sim 8.5$ kpc; David et al. 1997). The $N_H$ value derived with ASCA is also consistent with the one derived from the ROSAT PSPC and ART-P observations $(1.2–1.4) \times 10^{22}$ H atoms cm$^{-2}$; Grebeznev et al. 1996]. The rapid variability of the source was recently investigated by Wijnands & Van der Klis (1999a) using a short 10 ks RXTE observation performed between 1997 February and May (see below).

No accurate distance estimate exists so far. From the burst reported in Bazzano et al. (1997a) $(1.5 \times 10^{-8}$ ergs s$^{-1}$ cm$^{-2}$, 2–10 keV; Bazzano et al. 1997b), an upper limit of $\sim 10$ kpc can be derived (after bolometric corrections and assuming a blackbody of 2 keV for the burst). In the remainder of the paper, we will assume a distance of 8.5 kpc.

2.4. KS 1731$-$260

KS 1731$-$260 was discovered in 1988 October by TTM (Sunyaev et al. 1990) and then classified as a transient. KS 1731$-$260 is located in the Galactic center region, about 5° away from the Galactic nucleus and only 1° from the X-ray pulsar GX 1$+$4. Above the mean persistent level of 80 mcrab $(2.7 \times 10^{-10}$ ergs s$^{-1}$ cm$^{-2}$, 1–20 keV), TTM observed several X-ray bursts from KS 1731$-$260, thus indicating that it contains a weakly magnetized NS. The TTM spectrum was fitted by a thermal bremsstrahlung (hereafter TB$^3$) of 5.7 keV, absorbed through an $N_H$ of $2.2 \times 10^{22}$ H atoms cm$^{-2}$. Follow-up ROSAT and optical observations indicated that the source is a likely LMXB (Barret et al. 1998). The $N_H$ derived from the ROSAT PSPC all sky survey observations of $1.3 \times 10^{23}$ H atoms cm$^{-2}$ for a PL fit, is about a factor of 2 less that the value derived with TTM, thus possibly indicating intrinsic $N_H$ variations within the source. More recently, we observed KS 1731$-$260 with ASCA (1997 September 27) and confirmed the $N_H$ found by ROSAT (Narita, Grindlay, & Barret 2000). Additional X-ray observations can be found in Yamauchi &

3 Note that at such luminosities TB fits are unphysical because they imply emission measures $10^{53–60}$ cm$^{-3}$. The optically thin requirement leads to a size of $10^{16–17}$ cm for the cloud. These sizes are at least $\sim 100$–1000 times larger than the region of main energy release around a NS. This means that one should be cautious about the $N_H$ fitted, because its value depends critically on the shape assumed to fit the continuum.
Koyama (1990) and Aleksandovich et al. (1995). KS 1731–260 was detected only once in hard X-rays between 35 and 150 keV by SIGMA and has remained undetectable since then at these energies (Barret et al. 1992). Unfortunately, no simultaneous X-ray observations exist for the SIGMA detection.

RXTE first observed KS 1731–260 in 1996 July–August. It was then in its standard high state. These observations led to the discovery of a highly coherent 524 Hz periodic X-ray signal at the end of the contraction phase of an X-ray burst that showed photospheric expansion (Smith, Morgan, & Bradt 1997). This signal was tentatively interpreted as an indication of the NS spin (Smith et al. 1997). However, in the same data set, two simultaneous high-frequency quasi-periodic oscillations (HFQPOs) at 898 ± 3.3 Hz and 1158 ± 9 Hz were also found (Wijnands & Van der Klis 1997, see below). The frequency separation (260.3 ± 9.6 Hz, corresponding to 3.8 ms), which is equal to half the frequency of the burst oscillations was then interpreted as the true NS spin frequency (Wijnands & Van der Klis 1997).

In addition, assuming that the burst observed by RXTE reached the Eddington luminosity, a distance of 8.8 ± 0.3 kpc was derived for the source (Smith et al. 1997). At this distance, the implied source persistent X-ray luminosity at the time of the RXTE observations was $5.7 \times 10^{37}$ erg s$^{-1}$. Finally an $N_H$ value of $6 \times 10^{22}$ H atoms cm$^{-2}$ was derived for a TB fit of the RXTE PCA spectrum—a high value, significantly larger than the ASCA, ROSAT and TTM ones.

2.5. ASM Light Curves

The RXTE ASM long-term light curves of all four sources are shown in Figure 1 (for information about the RXTE/ASM, see Levine et al. 1996). The mean ASM count rates are 2.9 counts s$^{-1}$ (≈ 38 mcrab), 2.9 counts s$^{-1}$ (≈ 38 mcrab), 2.6 counts s$^{-1}$ (≈ 35 mcrab), and 11.3 counts s$^{-1}$ (≈ 150 mcrab) in the 2–12 keV range for 1E 1724–3045, GS 1826–238, SLX 1735–269, and KS 1731–260, respectively. Assuming a PL spectrum of photon index 2 and the source at the source distance, these values correspond to average 1–20 keV luminosities of $\sim 1.0 \times 10^{37}$ ergs s$^{-1} = 0.04L_{\text{Edd}}$, $8.8 \times 10^{36}$ ergs s$^{-1} = 0.03L_{\text{Edd}}$, and $1.3 \times 10^{37}$ ergs s$^{-1} = 0.05L_{\text{Edd}}$ for 1E 1724–3045, GS 1826–238, and SLX 1735–269, respectively. For KS 1731–260, assuming a thermal-like X-ray spectrum, the mean flux is about a factor of 5 larger: $\sim 4.9 \times 10^{37}$ ergs

![Figure 1](image-url)
These light curves provide the first confirmation of the low variability of SLX 1735–269, GS 1826–238, and 1E 1724–3045. In particular, for GS 1826–238, this together with independent measurements (e.g., Barret et al. 1995; In't Zand et al. 1999) indicate that since its discovery in 1988 the source has been a very stable accretor and certainly not a classical transient as previously thought. The light curve of KS 1731–260, shows also that the source is persistent but occasionally undergoes low-intensity states, which might be associated with episodes of hard X-ray emission.

3. OBSERVATIONS AND RESULTS

The PCA instrument consists of a set of five identical xenon proportional counter units (PCUs) covering the 2–60 keV energy range with a total area of about 6500 cm$^2$ (Bradt et al. 1993). The HEXTE instrument is made of two clusters of four NaI(Tl)/CsI(Na) phoswich scintillation detectors providing a total effective area of 1600 cm$^2$ in the 15–200 keV range (Rothschild et al. 1998). The two clusters rock alternately between the source and background fields to measure the background in real time. Special care has been taken to avoid the presence of any known X-ray sources in the background fields.

The rapid variability of the 4 sources has been investigated with the PCA SCIENCE EVENT data. Our spectral analysis is based on the STANDARD 2 data for the PCA. They provide count spectra each 16 s in 128 energy channels covering the 2–100 keV range. The FTOOLS used for PCA background estimation is PCABACKEST version 2.1b (released in 1998 October). For HEXTE, we also use the standard mode data. They provide 64 channel count spectra each 16 s. PCA spectra have been first accumulated for each PCU unit for integration times varying from ~1000 to ~2000 s, roughly equivalent to an orbit after filtering for good time intervals. In particular, PCA data recorded during and up to 30 minutes after the South Atlantic Anomaly passage have been removed using the FTOOLS 4.2 version of XTEFILT. PCA response matrices were then computed for each PCU using the FTOOLS PCARSP 2.36. We have then summed individual PCU spectra using ADDSPEC version 1.0.1, which combines not only the pulse height analyzer (PHA) files, but also the background PHA files, and computes the associated response matrices.

Note that this is about a factor of 4 larger that the effective area of the SIGMA imaging telescope for a source located in its fully coded field of view (Paul et al. 1991).

---

**Fig. 2.** Top: HEXTE 25–100 keV hard X-ray light curve with underneath the 2–40 keV PCA light curve of 1E 1724–3045 over the 4.5 day span of our observation. Bottom left: Color-color diagram (the soft color HR1 is the ratio 7–15 keV/2–7 keV, and the hard color HR2 is 15–40 keV/7–15 keV). Bottom right: Hardness-intensity diagram for the soft color. Only PCA data recorded with the five PCA units ON are shown (this explains the first gap in the PCA light curve while HEXTE was recording data).
For HEXTE, spectra were accumulated for each cluster with similar integration times to those used for the PCA. The latest response matrices have been used (hexte_97mar20c_pwa.rmf). Cluster A and B spectra were then combined together using ADDSPEC to get a single HEXTE spectrum averaged over the whole observation. The source and background light curves and spectra were corrected for dead-time effects using version 0.0.1 of HXTDEAD.

Version 10.00 of XSPEC (Arnaud 1996) has been used for the spectral fitting. When combining PCA and HEXTE spectra, the energy ranges of the fit were 2.5–25 keV for the PCA and above 25 keV and up to at most 150 keV for HEXTE. These energy ranges were selected to exclude the steepening of the PCA spectrum above 25 keV (in most spectra, it starts around 20 keV), as well as the flattening of the HEXTE spectrum toward low energies. Starting at 2.5 keV with the PCA implies that, in most cases, the \( N_H \) cannot be very well constrained. In each case, we have therefore set \( N_H \) to the most accurate value measured so far (i.e., by ASCA/ROSAT/BeppoSax). In order to account for the uncertainties in the relative calibration of the PCA and HEXTE experiments, we have also left the relative normalization of the two spectra as a free parameter of the model used.

To investigate the systematics in the PCA data and to validate our analysis scheme, we have first analyzed a 15 ks Crab observation (1997 March 22). We have found that to get acceptable fits it was necessary to add a systematic error to the data to reduce the effects of the imperfect knowledge of the instrument response near the K and L edges of xenon. These errors derived from looking at the residuals of the power-law fit are 0.5% between 2.5 and 15 keV, 1% between 15 and 25 keV and 2.5% above. Fitting the Crab spectrum between 2.5 and 25 keV thus yields a \( \chi^2_{\text{d.o.f}} \) of 1.0 (50 d.o.f.), a power-law index of 2.18, and a normalization at 1 keV of 13.5 photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) cm\(^{-2}\) (\( N_H = 3.3 \times 10^{21} \) cm\(^{-2}\) being frozen during the fit). The ratio between the data and the power law folded through the response matrix is shown in Figure 8. A similar level of systematics has been used by several groups (e.g., Rothschild et al. 1999; Wilms et al. 1999; Bloser et al. 2000). Based on this, before the fitting, we have combined quadratically to the Poisson errors of our data, with this level of systematics using the FTOOLS GRRPHA version 5.7.0. No systematic errors were added to the HEXTE data.
3.1. The RXTE Observations

The RXTE observations are summarized in Figures 2, 3, 4, and 5, for 1E 1724—3045, GS 1826—238, SLX 1735—269, and KS 1731—260. These figures represent the HEXTorr background-subtracted light curve (top panels), the PCA 2–40 background-subtracted light curve (middle panels), the PCA color-color diagram (soft color: 7–15 keV/2–7 keV, hard color 15–40 keV/7–15 keV [bottom left panel]), and a PCA hardness intensity diagram (bottom right panel). For clarity and homogeneity, the data from orbits contaminated by bursts have been filtered out (only data recorded with the five PCA units ON are shown).

The observation of 1E 1724—3045 started on 1996 November 4 \(T_0 = 11:54:39\) and was spread over more than 4 days. During the observation, an X-ray burst occurred on November 8 at 05:30:07 (UT). As said above for KS 1731—260, a few NSs exhibit nearly coherent pulsations during X-ray bursts. Sampling the burst profile each second, we have searched for such a coherent signal in both the SCIENCE EVENT and BURST CATCHER mode data. No significant signals were detected between 200 and 1500 Hz. Data from the orbit when the burst occurred and the next one have been removed from the present analysis. The source did not display any significant variability over the observation. In addition, looking at the color-color diagram, one can see that it was observed in a single spectral state (also see Olive et al. 1998). A single PCA spectrum averaged over the whole observation has thus been considered for the spectral analysis.

GS 1826—238 was observed between 1996 November 5 and 6, also for about 50 ks \(T_0 = 08:22:39\) UT. There are two bursts in the middle of the observation. As for 1E 1724—3045, no coherent pulsations were detected in those bursts. The time separation between the two bursts is \(T_5.6\) hr, consistent with the 5.76 hr \(T_1\) spread of 0.26 hr periodicity reported by Ubertini et al. (1999). In addition, from this periodicity, one expects a burst to have occurred \(T_1600\) s before the beginning of our observation. The tail of this burst is clearly seen in the first orbit of data. Data from this orbit, as well as from those contaminated by the two bursts, have been removed from the present analysis. The spectral analysis of these bursts and their impact on the persistent emission will be reported elsewhere. As shown in Figure 3 the source intensity varies by as much as \(\sim 10\%\) in the 2–40 keV range, but the source did not display significant spectral variability. As for 1E 1724—3045, a single PCA spectrum was then used in the spectral analysis. In the hard X-ray band, it is the brightest of the sources considered here (the count rate in HEXTorr Cluster A is 8.0 counts s\(^{-1}\) in the 25–100 keV range).
SLX 1735 – 269 was observed in 1997 October 10 ($T_\circ = 04:37:19$); its observation, which was scheduled for 50 ks, ended 2.5 days later. The mean PCA count rate is 165.5 counts s$^{-1}$ (2–40 keV), and this is the faintest of the four sources considered here. No X-ray bursts were observed. The source is clearly variable on minute time scales. However it is clear that these intensity variations are not accompanied by strong spectral changes, as the source remains in a limited region in the color-color diagram.

Finally, the observation of KS 1731 – 260 started on 1997 October 28 (22:20:15 UT), lasted for about 50 ks, and ended on October 30. In the PCA, KS 1731 – 260 has the largest count rate of the sources considered here. The so-called banana shape is clearly visible on the color-color and hardness intensity diagrams. It moves from the lower to the upper parts of the banana as the count rate increases (by up to $\sim 25\%$, 2–40 keV). Given the source variability, we have considered three PCA spectra in the spectral analysis, one for each day of the observation. It is detected by HEXTE only up to $\sim 50$ keV. No X-ray bursts were detected.

### 3.2. Timing Properties

The normalized power density spectra (PDSs) averaged over the whole observation of all four sources are shown in Figure 6. The first three sources show noise up to $\sim 200$ Hz. The integrated powers of these PDSs are, respectively, 29.1%, 26.1%, and 27.6% in the 2–40 keV band (0.005–300 Hz). In addition, they also show a break in the PDSs at low frequencies (typically around 0.1–0.2 Hz) and a QPO-like feature around 1 Hz. Although the complete analysis is still under way (for GS 1826 – 238 and SLX 1735 – 269), no strong HFQPOs were detected from any of these three systems. For 1E 1724 – 3045, for which a sensitive search has already been conducted, an upper limit of 2.5% on the rms of a 1000 Hz QPO has been derived (5–30 keV; Barret et al. 2000).

The PDS shown in Figure 6 for SLX 1735 – 269 is very similar both in shape and normalization to the one reported by Wijnands & Van der Klis (1999a) from a short RXTE observation performed in 1997 February–May. Although the source count rate did not change a lot during our observation (see Fig. 4), we have computed two PDSs for segments of the observation associated with the highest and lowest count rates: 172 counts s$^{-1}$ (156 counts s$^{-1}$) and 162 counts s$^{-1}$ (150 counts s$^{-1}$), 2–40 keV (2–16 keV), respectively. Fitting these two PDSs with broken power laws yields break frequencies of 0.15 $\pm$ 0.1 Hz and 0.08 $\pm$ 0.02 Hz, respectively. Thus, within our limited range of intensity variations, the break frequency decreased with the count rate, a behavior that is generally observed from atoll
sources (Van der Klis 1994). At the lowest count rate, Wijnands & Van der Klis (1999a) reported the opposite behavior between two segments of observations with count rates 141 and 113 counts s\(^{-1}\) (2–16 keV); \(v_{\text{Break}}\) increased from 0.11 to 2.3 Hz. Therefore, this means that, as in the case of the millisecond pulsar SAX J1808.4–3658 (Wijnands & Van der Klis 1998), it appears that \(v_{\text{Break}}\) correlates with the source count rate (the latter most likely tracking the mass accretion rate) down to a certain value, below which \(v_{\text{Break}}\) and the source count rate anticorrelate. For both SLX 1735–269 and the millisecond pulsar, this transition occurred at a luminosity of \(\sim (2-4) \times 10^{36}\) ergs s\(^{-1}\) (3–25 keV).

KS 1731–260 is characterized by weaker variability with an integrated power of \(\sim 3.0\%\) (2–40 keV). Its PDS can be approximated by a PL of index \(\alpha = 1.3\) on which a QPO centered at 7.6 \(\pm\) 0.7 Hz is superposed (FWHM = 3.1 \(\pm\) 2.0 Hz for a Gaussian fit). This QPO is very similar to the so-called Horizontal branch QPO observed in Z sources. In addition, at higher frequencies, for the segment of the observation performed on October 28 (i.e., at the lowest count rate \(\sim 1050\) counts s\(^{-1}\), 5–30 keV), we have detected at the 4.7 \(\sigma\) level a HFQPO centered at \(\sim 1200 \pm 10\) Hz (FWHM = 45.0 \(\pm\) 20 Hz, rms = 2.5 \(\pm\) 0.4\%). This is the highest HFQPO ever detected from KS 1731–260. No HFQPOs were detected in the subsequent observations performed on October 29 (1285 counts s\(^{-1}\)) and 30 (1355 counts s\(^{-1}\)). We have derived an upper limit of \(\sim 2\%\) on the rms of any HFQPOs around 1000 Hz for the October 29 and 30 observations. Our October 28 detection follows the correlation between the frequency of the HFQPO (\(v_{\text{HFQPO}}\)) and the count rate, as well as the anticorrelation between \(v_{\text{HFQPO}}\) and rms presented in Wijnands & Van der Klis (1997).

3.3. Spectral Fitting

Previous observations of similar NSs have shown that their broadband spectra can be generally fitted by the sum of two components (Mitsuda et al. 1984, 1989; White, Stella, & Parmar 1988). The first one is soft, contributes to the spectrum mainly below 10 keV, and is modeled by a PL (below 20 keV). However, when high-energy coverage exists above 30 keV (e.g., with BeppoSax and RXTE), Comptonization models provide more physical fits (e.g., Guainazzi et al. 1998; In’t Zand et al. 1999). The Comptonization process is speculated to take place in a scattering corona located somewhere in the system: around the NS (e.g., optically thin boundary layer, spherical corona) or above the disk. In some cases, a relatively strong iron K\(\alpha\) line (6.4 keV) is also observed above the continuum (e.g., White et al. 1986). In a few cases (e.g., 4U 1608–522,
Yoshida et al. 1993; SAX J1808.4 – 3658, Gilfanov et al. 1998), such a line is accompanied by a broad absorption like feature, interpreted as partial absorption or reflection by a cold or weakly ionized medium of the intrinsic PL component. Hereafter we report on the results of the spectral analysis of our observations, placed in the framework of these previous results.

3.3.1. 1E 1724 – 3045

Preliminary results of the analysis of the 1E 1724 – 3045 spectral data can be found in Olive et al. (2000). In the present analysis, N_\beta has been set to the ASCA/BeppoSax value (i.e., 1.2 \times 10^{22} \text{ H atoms cm}^{-2}). Driven by the recent BeppoSax results, we have found that the broadband spectrum of 1E 1724 – 3045 can be adequately described by the sum of two components: a soft and a hard Comptonized component, the best-fit parameters are strikingly similar to those found from the point of view of its energy spectrum. For the soft component, the best-fit parameters are significantly similar to those derived from the BeppoSax observations.

Independently of the model fitting the continuum, an excess around 6 keV seems to remain in the residuals. Assuming that it results from iron K\beta\alpha\beta fluorescence (6.4 keV) and that it is narrow (c_{\text{FWHM}} = 0.1 \text{ keV}), the COMPTT + BB + line model yields a \chi^2 of 79.9 (80 d.o.f.).

TABLE 1

| Parameter | C + BB + L | C + MCD + L |
|-----------|------------|-------------|
| kT_e (keV)| 28.1^{+3.0}_{-1.0} | 25.6^{+2.1}_{-1.1} |
| kT_{\text{bb}} (keV) | 1.1^{+0.1}_{-0.1} | 1.6^{+0.2}_{-0.2} |
| \tau | 2.9^{+0.3}_{-0.2} | 3.3^{+0.3}_{-0.3} |
| kT_{\text{bb}}, kT_{\text{in}} (keV) | 0.6^{+0.1}_{-0.1} | 1.2^{+0.1}_{-0.1} |
| R_{\text{bb}}, R_{\text{in}}(\cos \theta)^{1/2} (km) | 10.1^{+1.1}_{-1.1} | 2.8^{+0.2}_{-0.2} |
| Equivalent width (eV) | 21^{+1.0}_{-1.0} | 27^{+1.0}_{-1.0} |
| \chi^2 (d.o.f.) | 79.9 (80) | 85.7 (80) |
| F_{1-20 keV} (10^{-9} \text{ ergs s}^{-1} \text{ cm}^{-2}) | 1.52 | 1.58 |
| F_{20-200 keV} (10^{-9} \text{ ergs s}^{-1} \text{ cm}^{-2}) | 0.90 | 0.91 |
| f_{\text{bb}} (%) | 14.4 | 27.2 |

Notes.—N_\beta has been set to 1.2 \times 10^{22} \text{ H atoms cm}^{-2}. The C + BB + L model is COMPTT + blackbody + a 6.4 keV narrow line (c_{\text{FWHM}} = 0.1 \text{ keV}), whereas C + MCD + L is COMPTT + multicolor disk blackbody + a 6.4 keV narrow line. kT_e is the electron temperature, kT_{\text{bb}} is the temperature of the seed photons in the COMPTT model, \tau is the optical depth of the spherical scattering cloud, kT_{\text{in}} is the temperature of the blackbody, and kT_{\text{bb}} is the inner disk color temperature derived from the MCD model. f_{\text{bb}} is the equivalent radius of the blackbody, whereas R_{\text{bb}}, R_{\text{in}}(\cos \theta)^{1/2} is the projected inner disk radius (Mitsuda et al. 1994); they are both scaled at the source distance (6.6 kpc). The equivalent width is the contribution of soft component (BB or MCD) to the total luminosity computed in the 1-200 keV range. Errors in all the tables are quoted at the 90\% confidence level (\chi^2 = \chi^2 + 2.7).

Fig. 7.—(Top) Data and folded model, (center) residuals, and (bottom) unfolded spectrum, showing the Comptonized (COMPTT) component (dashed line), the multicolor disk blackbody model (dot-dashed line), and the Gaussian line (dotted line) of 1E 1724 – 3045.
(COMPTT + BB + L), the residuals, and the unfolded spectrum of 1E 1724–3045.

For comparison with SIGMA data (35–200 keV), we have fitted the HEXTE data alone in the 25–150 keV range. Although the fit is not satisfactory because of the presence of a clear high-energy cutoff (~ 70 keV), a PL fit yields a photon index of 2.7 ± 0.1, to be compared with the time-averaged value observed by SIGMA (3.0 ± 0.3, Goldwurm et al. 1993, 1994, 1995). Fitting the 2.5–25 keV PCA spectrum with a simple PL (note an acceptable fit) yields a photon index of ~ 2.0. We therefore conclude that the steepness of the hard tail observed by SIGMA was artificial and due to the presence of a high-energy cutoff around 60–70 keV. We have also fitted the continuum with the relativistic Comptonization model developed by Poutanen & Svensson (1996; COMPPS in XSPEC). For the Comptonized tail, this yields best-fit parameters of 35 keV for $kT_e$ and 2.1 for $\tau$ (spherical geometry assumed).

From this observation, we derive $L_{1-20}$ keV = 8.1 x 10$^{36}$ ergs s$^{-1}$, and $L_{20-200}$ keV = 4.8 x 10$^{36}$ ergs s$^{-1}$ ($d = 6.6$ kpc). $L_{1-20}$ keV is consistent with the time-averaged value derived from the ASM light curve.

3.3.2. GS 1826–238

For GS 1826–238, we have again set $N_H$ to the value observed by ROSAT and BeppoSax (0.5 x 10$^{22}$ H atoms cm$^{-2}$). To illustrate the complexity of the spectral shape, in Figure 8 we show the ratio between the PCA data and a PL model folded through the PCA response matrix. There is a clear excess around 6.0 keV. First, of the single-component models, the CPL is the one that provides the best fit. This yields a cutoff energy at ~ 95 keV and a photon index of 1.7 ($\chi^2 = 195.0$ for 87 d.o.f). A fit using a Comptonization model (e.g., COMPST in XSPEC) yields $kT_e$ of 20 keV and an equivalent depth of 4.6. Adding a narrow 6.4 keV line (S$_{Fe} = 0.1$ keV) to account for the feature of Figure 8 improves the fit ($\chi^2 = 149.4$ for 86 d.o.f) but still, the residuals show systematic deviations that indicate that this model is not the right description of our data.

Since a reflected component had been found in a combined analysis of the OSSE and Ginga data (Strickman et al. 1996), we have tested for the presence of such a component by adding an absorption edge at 7.1 keV. This leads to a significant decrease of $\chi^2$ [$\chi^2 = 100.5$ for 85 d.o.f, $F_m = 41.3$, $P(F > F_m) \geq 7.9 \times 10^{-9}$]. Thus we have substituted the CPL model by the XSPEC PEXRAV model (Magdziarz & Zdziarski 1995), which is the sum of a CPL plus a Compton reflected component. The inclination angle to the source is unknown, but since GS 1826–238 is not a dipper, we have assumed a standard value of $\theta = 60^\circ$, and we leave the reflection scaling factor as a free parameter (we assumed solar abundance for the reflecting material). This yields a reflection scaling factor of ~ 0.20 and a narrow 6.4 keV line ($\sigma_{Fe} = 0.1$ keV) of equivalent width 37 eV ($\chi^2 = 97.1$, 85 d.o.f.). The significance of the reflection component is very high [$F_m = 45.4$, $P(F > F_m) \geq 1.8 \times 10^{-6}$]. Leaving the line energy and its width as free parameters of the model, we get $\chi^2 = 85.2$ (83 d.o.f) with the line parameters: $\sigma_{Fe} = 0.48$ keV, centroid energy at 6.1 $\pm 0.1$ keV (90% confidence level, still consistent with a fluorescent iron K$\alpha$ line), and an equivalent width of 50 eV. This decrease of $\chi^2$ is significant at the level of 99.7% [$F_m = 6.0$, $P(F > F_m) = 0.003$], we therefore conclude that this is the best fit to our data. As a further step, we have tried a reflection model including ionization: PEXRIV model in XSPEC (Magdziarz & Zdziarski 1995). This model fits the data as well as the PEXRAV model ($\chi^2 = 95.5$, 84 d.o.f) and yields a disk ionization parameter consistent with 0. Therefore, with both models, our data are consistent with reflection from a cool neutral medium.

We have also reanalyzed the Ginga spectrum of GS 1826–238 used in Strickman et al. (1996) and Zdziarski, Lubinski, & Smith (1996). The reflection component is highly significant, and it is also consistent with coming from a neutral medium. A fit with a simple power law and a 6.4 keV narrow line yields $\chi^2 = 39.6$ for 31 d.o.f, while adding the reflection component yields $\chi^2 = 16.1$ for 29 d.o.f. [$F_m = 21.2$, $P(F > F_m) = 2.1 \times 10^{-6}$]. The best-fit parameters are $\Gamma = 1.88 \pm 0.05$, $f_{refl} = 0.8 \pm 0.3$, and an equivalent width for the iron line of 15 eV.\footnote{The evidence for a reflection component is very strong in both the RXTE and Ginga data. It is therefore quite puzzling that no such component has been reported so far from the two BeppoSax observations performed, while GS 1826–238 was at a similar intensity level ($7.7 \times 10^{-10}$ ergs s$^{-1}$ cm$^{-2}$ for RXTE, as opposed to $5.5 \times 10^{-10}$ ergs s$^{-1}$ cm$^{-2}$ for BeppoSax (2–10 keV), Del Sordo et al. 2000; In't Zand et al. 1999). We are currently investigating this issue, searching for instrumental effects, sensitivity limits, and systematic errors in the fitting the continuum shape.}

There is no soft component in the source spectrum. With the PEXRAV model, we have set a 90% confidence limit of about 1% on the fraction of 1–200 keV luminosity in the soft component modeled by a 1.5 keV BB component. The
we Ðx at 1.5
considered the HEXTE data only up to 50 keV. In our Ðts of the HEXTE spectrum is not as good. For that reason, we
fainter than the other two sources, so the statistical quality was observed in a hard state. However, it was a factor of 2
D

\begin{table}[h]
\centering
\begin{tabular}{lcc}
\hline
Parameter & CPL+L & CPL+R+L \\
\hline
\(\Gamma\) & 1.70\,^\pm\,0.01 & 1.72\,^\pm\,0.01 \\
\(E_{\text{cutoff}}\) (keV) & 98.7\,^\pm\,7.0 & 90.0\,^\pm\,8.0 \\
\(f_{\text{soft}}\) & 0.15\,^\pm\,0.03 & 0.15\,^\pm\,0.04 \\
Line energy (keV) & 6.4 (fixed) & 6.1\,^\pm\,0.2 \\
\(\sigma_{\text{Fe}}\) (keV) & 0.1 (fixed) & 0.48\,^\pm\,0.23 \\
Equivalent width (eV) & 36\,^\pm\,15 & 50\,^\pm\,15 \\
\(\chi^2\) (d.o.f) & 149.4 (86) & 85.2 (83) \\
\(F_{1-20\text{ keV}}\) \((10^{-9}\) ergs s\(^{-1}\) cm\(^{-2}\)) & 1.43 & 1.44 \\
\(F_{20-200\text{ keV}}\) \((10^{-9}\) ergs s\(^{-1}\) cm\(^{-2}\)) & 1.17 & 1.16 \\
\hline
\end{tabular}
\caption{Best-Fit Spectral Results for GS 1826–238}
\end{table}

results of the best Ðt using the CPL + line + reÑection model are given in Table 2. The data and folded model, the residuals, and the unfolded spectrum of GS 1826–238 are shown in Figure 9.

For comparison with hard X-ray observations of similar systems, we have Ðtted the HEXTE spectrum with a PL. Although the Ðt is poor because of the presence of a clear cutoff in the spectrum, one gets a photon index of \(\Gamma = 2.3 \pm 0.2\), similar to the value derived for 1E 1724–3045. Fitting the hard tail with the COMPPS model yields \(k_{\text{cutoff}} = 41\) keV and \(\Gamma = 1.9\).

For this observation, one derives \(L_{1-20\text{ keV}} = 8.4 \times 10^{36}\) ergs s\(^{-1}\) and \(L_{20-200\text{ keV}} = 6.9 \times 10^{36}\) ergs s\(^{-1}\) \((d = 7\) kpc). \(L_{1-20\text{ keV}}\) is very close to the time-averaged value derived from the ASM light curve.

### 3.3.3. SLX 1735–269

A preliminary report of the spectral analysis of SLX 1735–269 can be found in Skinner et al. (2000). As in the cases of GS 1826–238 and 1E 1724–3045, SLX 1735–269 was observed in a hard state. However, it was a factor of 2 fainter than the other two sources, so the statistical quality of the HEXTE spectrum is not as good. For that reason, we considered the HEXTE data only up to 50 keV. In our Ðts we Ðx \(N_{\text{H}}\) at \(1.5 \times 10^{22}\) H atoms cm\(^{-2}\), found in David et al. (1997), as the ASCA data are more sensitive to this parameter. We have Ðrst Ðtted the PCA + HEXTE spectrum of SLX 1735–269 with a simple PL. The Ðt is not good (\(\chi^2\) 2 d.o.f \(\approx 6.5\)) but shows clear evidence for a broad feature around 6.4 keV (see Fig. 8). As no iron line was seen in the ASCA data, and because of the relative faintness of the source, we have Ðrst considered the possibility that the line might not be from the source but might represent the Þux within the PCA 1° field of view from the Galactic bulge diffuse emission. We have therefore included in our model a contribution from the spectrum given by Valinia & Marshall (1998) for their region 2, which includes this part of the sky. Refitting the data with this component affects the shape of the residuals at low energies (\(\leq 5\) keV); they now clearly show the presence of a soft component and reveal that the broad feature between 6–7 keV cannot all be accounted for by the diffuse emission, meaning that there remains a need for a signiÐcant contribution from the source to the line. Such a line was also needed in the data analyzed by Wijnands & Van der Klis (1999a). The soft component was Ðtted with an MCD (although the BB model Ðts the data equally well), whereas the line contribution from SLX 1735–269 was modeled by a Gaussian centered at 6.4 keV. This leads to a \(\chi^2\) of 45.2 (59 d.o.f), and thus the addition of the line and soft component is statistically signiÐcant based on our \(F\)-test. The equivalent width found (67 eV if the line is narrow, \(\sigma_{\text{Fe}} = 0.1\) keV) is well below the upper limits of 150 eV (\(\sigma_{\text{Fe}} = 0.1\) keV) derived by David et al. (1997) using ASCA SIS data.

However, by looking at the residuals above \(\sim 7\) keV the data show systematic deviations with an edgelike shape. An edge around these energies is suggestive of the presence of a

\footnote{For SLX 1735–269, the \(\chi^2\) associated with the best Ðts are lower than 1 (see Table 3). This makes naturally questionable the results of our \(F\)-test. Similarly, the errors computed on the best-Ðt parameters should not be considered as true 90% uncertainties (these errors are computed under the assumption that the errors on the data are Poissonian). The low \(\chi^2\) indicates certainly that for SLX 1735–269, which is the faintest of the four sources, the systematics assumed are too large. However, for consistency in the analysis, we have chosen to set them to the values used for the other sources.}
reflection component. We have therefore first substituted the PL model with the PEXRAV model in XSPEC (assuming no energy cutoff in the model and a 6.4 keV line with a $\alpha_p = 0.1$ keV, an inclination angle of 60°). This leads to $\chi^2 = 31.4$ (58 d.o.f.), indicating that the presence of a reflected component is significant at a level greater than 99.99% [F$^m_m = 23.1$, $P(F > F_m) = 1.1 \times 10^{-3}$]. The solid angle inferred is $\sim 0.26$, and the line equivalent width is 47 eV. Whether or not the reflector is ionized has been tested by using the PEXRIV model. The statistical quality of the data does not allow us to determine the line energy simultaneously with the Compton reflected component. We have therefore first substituted the PL model with the PEXRIV model in XSPEC allowing for ionization (PEXRIV in XSPEC), an MCD, and a narrow 6.4 keV line ($\alpha_p = 0.1$ keV). The cutoff energy in PEXRIV has been set to 200 keV and frozen during the fit. $\xi$ is the ionization parameter in PEXRIV. The contribution for the Galactic diffuse component has been modeled by a Raymond-Smith model of 3.4 keV (normal abundance) and normalization factor of $1.5 \times 10^{-2}$ in XSPEC units.

In the absence of any cutoffs in the useful energy range of the present measurements, Comptonization models cannot really be used. We note, however, that a Comptonization model for which the electron temperature would be $\sim 30$ keV (as seen in 1E 1724−3045) could fit the continuum as well as the PL. This would yield an optical depth of $\sim 3$ for the scattering cloud. Similar results were obtained by combining simultaneous ASCA and SIGMA data (Goldwurm et al. 1995). The best-fit parameters are listed in Table 3, while the data and folded model, the residuals, and the unfolded spectrum are shown in Figure 10.

For this observation, we derive $L_{1-20}$ keV $= 6.0 \times 10^{36}$ ergs s$^{-1}$ and $L_{20-200}$ keV $= 3.5 \times 10^{36}$ ergs s$^{-1}$ ($d = 8.5$ kpc). $L_{1-20}$ keV is about a factor of 2 lower than the time-averaged value derived from the ASM light curve.

### Table 3

| Parameter | CPL + MCD + L | CPL + MCD + R + L |
|-----------|---------------|-------------------|
| $\Gamma$  | $2.06^{+0.03}_{-0.01}$ | $2.09^{+0.03}_{-0.01}$ |
| $kT_e$ (keV) | $0.53^{+0.07}_{-0.04}$ | $0.44^{+0.10}_{-0.04}$ |
| $R_\text{in}$ (km) | $9.4^{+3.4}_{-1.2}$ | $17.0^{+6.6}_{-0.4}$ |
| $\xi$ | $0.28^{+0.09}_{-0.12}$ | $0.70^{+0.40}_{-0.12}$ |
| Equivalent width (eV) | $67^{+15}_{-15}$ | $39^{+14}_{-14}$ |
| $\chi^2$ (d.o.f) | 45.2 (59) | 28.4 (57) |
| $F_{1-20}$ keV ($10^{-9}$ ergs s$^{-1}$ cm$^{-2}$) | 0.72 | 0.75 |
| $F_{20-200}$ keV ($10^{-9}$ ergs s$^{-1}$ cm$^{-2}$) | 0.39 | 0.30 |
| $f_{\text{in}}$ (%) | 9.0 | 12.6 |

**Notes:** $N_H$ has been set to $1.5 \times 10^{22}$ H atoms cm$^{-2}$. The first model is the sum of CPL + MCD and a 6.4 keV narrow line. The best-fit model is the sum of a CPL and its Compton reflected component (R) allowing for ionization (PEXRIV in XSPEC), an MCD, and a narrow 6.4 keV line ($\alpha_p = 0.1$ keV). The cutoff energy in PEXRIV has been set to 200 keV and frozen during the fit. $\xi$ is the ionization parameter in PEXRIV. The contribution for the Galactic diffuse component has been modeled by a Raymond-Smith model of 3.4 keV (normal abundance) and normalization factor of $1.5 \times 10^{-2}$ in XSPEC units.
3.3.4. **KS 1731−260**

KS 1731−260 was observed in a high state, and its spectrum is clearly much softer than the other three sources examined before. We have assumed the $N_{\text{H}}$ measured by *ROSAT* and *ASCA* (i.e., $1.2 \times 10^{22}$ H atoms cm$^{-2}$). As the source intensity increased smoothly during our 3 day observation and its intensity variations are accompanied by spectral variations (see Fig. 5), as said above we have made a PCA spectrum for each of the three days. These PCA spectra were fitted simultaneously with a single HEXT spectrum averaged over the whole observation to increase the statistics at high energies.

We first analyzed the October 28 spectrum. As there is a clear cutoff in the spectrum around 10 keV, we have first fitted the continuum with a simple Comptonization model (COMPST). This model alone is clearly rejected ($\chi^2 \geq 977$ for 55 d.o.f). This is mainly due to the presence of a broad feature again centered around 6.4 keV. We have therefore added an iron K fluorescence line (6.4 keV) and fitted its width and intensity. This improves the fit significantly ($\chi^2 = 156.2$ for 53 d.o.f). However, looking at the residuals indicates that the low-energy part of the spectrum is not well accounted for. Because a soft component (either a blackbody or a disk blackbody) is usually observed in similar systems (e.g., White et al. 1988), we have included such a component in the fit. This again improves the fit [$\chi^2 = 48.6$ for 51 d.o.f., $F_\text{m} = 56.5$, $P(F > F_\text{m}) = 1.2 \times 10^{-13}$] for addition of the BB model. We have tried to fit the hard component with an MCD model (Mitsuda et al. 1984), instead of using COMPST, but the fit is rejected, as the reduced $\chi^2$ exceeds 4. On the other hand, the soft component could equally well be fitted with an MCD. For both models, the equivalent radius of the BB and the projected inner disk radius of the MCD are small; $R_{\text{BB}} \leq 5$ km and $R_{\text{MCD}}(\cos \theta)^{1/2} \leq 4$ km, respectively, smaller than the NS radius, or the expected inner disk radius around a NS (especially if the NS is as massive as $2M_\odot$, see above). This does not mean however that the models can be ruled out, because, for instance, only a small fraction of the NS surface could be involved in the emission, or alternatively some fraction of the disk flux could be intercepted and scattered up in a corona.

We have also tried the COMPTT model for the Comptonized component. However, the temperature for the seed photons ($kT_\text{w}$) is typically 0.2−0.3 keV, and is therefore unreliable since the peak of the Wien law, at $3kT_\text{w}$, is also below 2.5 keV (the peak is needed for $kT_\text{w}$ to be determined reliably). For the Comptonizing cloud, $kT_e$ are consistent between COMPTT and COMPST, whereas $\tau$ is a factor of $\sim 2$ lower for COMPTT than for COMPST (spherical geometry assumed).

The broadening of the line (due to Comptonization?) is significant. Assuming that the line is narrow ($\sigma_F = 0.1$ keV), we obtain a larger $\chi^2$ (87.1 for 52 d.o.f). The hypothesis that the line is narrow is therefore rejected at more than 99.99% confidence level ($F_\text{m} = 40.4$, $P(F > F_\text{m}) = 5.6 \times 10^{-8}$). If one leaves the energy of the line as a free parameter, its value tends to move toward lower energies ($\sim 6.2$ keV, $\chi^2 = 46.1$ for 50 d.o.f). However, this shift of the line energy is not significant [$F_\text{m} = 2.1$, $P(F > F_\text{m}) = 0.14$].

If an iron line of equivalent width $\sim 100−150$ eV is present, one might expect to detect also a Compton reflection component. First adding an edge at 7.1 keV (cool iron) never improved the fit significantly (significance always lower than 95%, the line energy and width were kept fixed). Similarly, we tried to fit the data with the PEXRAV model, as a substitute to the COMPST model. This never improved the fit either. The nondetection of such a component might be simply related to the curvy shape of the spectrum (in particular the continuum is not a CPL as assumed in PEXRAV); reflection is easier to observe when the continuum is PL-like (Note that if there is indeed a reflection component this will affect the fitted parameters for the continuum and hence the strength of the iron line).

The same model is also the best fit of the October 29 and 30 spectra. In Table 4, we list the best-fit parameters for the COMPST + BB + line and COMPST + MCD + line models. The data and folded model, the residuals, and unfolded spectrum of KS 1731−260 for October 28 are shown in Figure 11.

For KS 1731−260, $L_{1−20}$ keV was $\sim 8.0 \times 10^{37}$ ergs s$^{-1}$ at the beginning of the observation and reached $\sim 9.1 \times 10^{37}$ ergs s$^{-1}$ at the end ($d = 8.8$ kpc). Such X-ray luminosity is slightly larger than the time-averaged ASM value. Throughout the observation, $L_{20−200}$ keV contributed just at the level of $\sim 1\%$ to the 1−200 keV luminosity of the source.

![Figure 11](image-url)  
**Figure 11.** (Top) Data and folded model, (center) residuals, and (bottom) unfolded spectrum of KS 1731−260 for the October 28 observation, showing the contribution from the COMPST component (dot-dashed line), the blackbody (dotted line), and the broad iron line (dashed line).
**4. DISCUSSION**

We have here reported RXTE PCA + HEXTE timing and spectral observations of four type I X-ray bursters (hence NSs). In the remainder, first we discuss their timing properties, then their broadband spectral properties, and finally issues concerning possible differences between BHs and NSs.

**4.1. Timing Properties**

1E 1724 – 3045, SLX 1735 – 269, and GS 1826 – 238 were in a so-called low state (LS), whereas KS 1731 – 260 was in a high state (HS). The LS sources all have very similar PDSs, characterized by high-frequency noise (HFN, or flat-top noise; Van der Klis 1994) with large rms amplitudes (30%, 2 – 40 keV). 1E 1724 – 3045 and SLX 1735 – 269 are each characterized by the presence of a ~1 Hz QPO and a break (at \( v_{\text{break}} \)) at 0.1 – 0.2 Hz. For GS 1826 – 238, depending on the modeling of the PDS, \( v_{\text{break}} \) ~ 0.02 Hz or ~0.2 Hz, and \( v_{\text{QPO}} \) ~ 0.2 or ~1.0 Hz. KS 1731 – 260 has a very different PDS, displaying both very low frequency noise (VLFN) and a QPO at different PDS, displaying both very low frequency noise whereas KS 1731 is consistent with those of atoll sources at varying luminosities, according to the terminology defined by Hasinger & Van der Klis (1989).

**4.1.1. Origin of the High-Frequency Noise?**

The high-frequency noise is seen only in sources displaying significant hard X-ray emission (all sources except KS 1731 – 260) and hence must be related to the existence of a hot scattering cloud. This noise in the PDS is very similar in shape and normalization to that seen from LS BHs, strongly suggesting that the same physical mechanism is responsible for the spectrum and variability in these systems. Since the spectral shape strongly suggests thermal Compton up scattering, then the variability must have something to do with varying the seed photons, the optical depth, or the dissipation in the hot region.

The overall PDS shape can be described by a superposition of randomly occurring flares (or "shots"), generally with some distribution of event durations. Such "shot noise" models can give a good description of the PDS (Lochner, Swank, & Szymbkwiai 1991, and references therein; Miyamoto et al. 1992; Nowak, Wilms, & Dove 1999; Olive et al. 1998) but are only a phenomenological, rather than a physical, description of the variability. To get a physical description requires associating the shots in the Comptonization cloud.

The simplest variability to envisage is a change of the soft photon input. Thermal Comptonization involves multiple scattering of these seed photons on the hot electrons, so the spectrum at lower energies responds first, followed after several scattering timescales by the higher energy spectrum. Such models predict that there should be time lags between the hard and soft energy bands, but that these lags (which are simply a measure of the size of the scattering cloud) should be constant irrespective of whether the input variability was a short flare or a longer event. This directly conflicts with the observed lags in the BHs (Miyamoto et al. 1988) and the NSs (Ford et al. 1999), which clearly show longer lags for longer timescale variability (Miyamoto et al. 1998).

A satisfactory explanation of the long timescale lags is difficult. If the variability arises from varying the seed photons, then the length of the lag directly implies that the region is large. This led Kazanas, Hua, & Titarchuk (1997) to develop the extended atmosphere Comptonization model (see also Hua, Kazanas, & Cui 1999). This assumes a source of white noise at the center of the scattering cloud that has a density profile \( n(r) \propto 1/r \) out to radii of a few light seconds. Their inhomogeneous density distribution appears to match the observed time lags, and source spectra, but the physical situation is very hard to envisage. The majority of the gravitational potential energy is close to the compact object, so how can this power a hot corona whose size is many orders of magnitude larger? Another weakness of that model, is that it produces different PDSs at different energies, contrary to what is observed (e.g., Nowak et al. 1999; Olive et al. 1998).

An alternative model that can fit the PDSs and time lags but with a small source size has been developed by Poutanen & Fabian (1999), who associate the shots with magnetic flares above a cold accretion disk and use the spectral evolution of the flares to produce the long lags. The flare begins with electrons being heated but the background disk seed...
photon density is high, so the early time flare spectrum is soft. As the heating progresses, the energy dissipated in the flare dominates that of the disk, so the spectrum becomes hard. The drawback with such models is that they rely on details of the magnetic dissipation, which are not well known. Nonetheless, it is encouraging that at least under some circumstances the lags and PDSs can be matched by the envisaged small source.

4.1.2. Origin of Low-Frequency QPOs?

The origin of the ~1 Hz QPO (at $v_{\text{qpo}}$) in the LS sources, once suspected to be a BH signature, is also unknown and is not accounted for by the above models. Chen & Taam (1994) have proposed that they might arise from disk luminosity oscillations resulting from thermal viscous instabilities developing within the inner disk region. Vikhlinin, Churazov, & Gillanov (1994) have also suggested that they could result from a weak interaction between the shots when the instability is triggered in a region of stable energy supply. To keep the energy released constant on large timescales, the appearance of a strong shot should affect the amplitude and the probability of occurrence of subsequent shots. Recently, developing a model specific for NSs (i.e., not accounting for the similarities between BHs and NSs), Titarchuk & Osherovich (1999) have associated the QPOs with radial oscillations in a boundary layer.

It has been shown that in many sources there exists a strong correlation between $v_{\text{break}}$ and $v_{\text{qpo}}$ (Wijnands & Van der Klis 1999b). Our three LS sources follow this correlation. This correlation suggests that the longest fluctuations (scaling as $v_{\text{break}}$) and the QPOs are related to the same unknown physical mechanism or are produced in regions interacting with each other. Since the same correlation is observed among BHs and Z-sources, this mechanism could result from a weak interaction between the shots when the instability is triggered in a region of stable energy supply. To keep the energy released constant on large timescales, the appearance of a strong shot should affect the amplitude and the probability of occurrence of subsequent shots. Recently, developing a model specific for NSs (i.e., not accounting for the similarities between BHs and NSs), Titarchuk & Osherovich (1999) have associated the QPOs with radial oscillations in a boundary layer.

It has been shown that in many sources there exists a strong correlation between $v_{\text{break}}$ and $v_{\text{qpo}}$ (Wijnands & Van der Klis 1999b). Our three LS sources follow this correlation. This correlation suggests that the longest fluctuations (scaling as $v_{\text{break}}$) and the QPOs are related to the same unknown physical mechanism or are produced in regions interacting with each other. Since the same correlation is observed among BHs and Z-sources, this mechanism could result from a weak interaction between the shots when the instability is triggered in a region of stable energy supply. To keep the energy released constant on large timescales, the appearance of a strong shot should affect the amplitude and the probability of occurrence of subsequent shots. Recently, developing a model specific for NSs (i.e., not accounting for the similarities between BHs and NSs), Titarchuk & Osherovich (1999) have associated the QPOs with radial oscillations in a boundary layer.

4.1.3. Spectral States and High-Frequency QPOs

Finally, in the three sources displaying high-frequency noise and hard X-ray tails, no HFQPOs (above 300 Hz) are detected (e.g., 1E 1724−3045; Barret et al. 2000). More generally, it seems that no HFQPOs are seen when $v_{\text{break}}$ is low ($\leq 6−7$ Hz; e.g., 4U 1705−44, Ford et al. 1998). The lack of HFQPOs might therefore be related to the presence of a hot scattering corona. Smearing of the HFQPO signal in such a corona is a possible mechanism, which is however invoked at higher accretion rates (i.e., for larger optical depth $\tau \gtrsim 5$, cooler corona; Brainerd & Lamb 1987). This might indeed explain the disappearance of the HFQPOs after it has reached saturation (i.e., when the inner disk is at the last stable orbit, e.g., 4U 1820−30; Bloser et al. 2000), or more generally when the source enters the upper branch of the banana state (Miller, Lamb, & Psaltis 1998). The anti-correlation between the QPO amplitude and the QPO frequency observed in KS 1731−260 (see above) is consistent with this picture (note that there is a weak indication that the optical depth derived from the spectral fitting increases when the source luminosity increases, see Table 4). For the LS sources, from the spectral analysis, we have derived an optical depth of a few for the Comptonizing cloud. Could that cloud, through smearing, account for the lack of HFQPOs? Using our upper limit, one can set a lower limit on the size of the scattering region. If the radiation is scattered, the rms amplitude at infinity ($A_{\infty}$) of a luminosity oscillation with frequency $v$ and amplitude $A_0$ at the center of a spherical region of radius $R_c$ and optical depth $\tau$ is $A_{\infty} \approx (2^{1/2}v^{-1/2} - e^{-v})A_0$, where $x = (3\pi v R_c^2 / v)^{1/2}$. The frequency of the oscillation; Kylafis & Phinney 1989; Miller et al. 1998). For a beaming oscillation, the attenuation is stronger (because of the fact that the scattering process tends to isotropize the photon distribution), and the first term of the previous equation has to be multiplied by a factor of $2(1 + x)$ (Kylafis & Phinney 1989). Let us first consider $v = 300$ Hz from the previous expression; taking $A_{\infty} = 2.5\%$ (our upper limit) and assuming $R_c = 200$ km, one can set upper limits of ~4% and ~6% on $A_0$ for a luminosity and beaming oscillations, respectively. For a signal at 1000 Hz, these upper limits become 12% and 20%, respectively. Alternatively, if we assume $A_0 = 10\%$, for the signal to be attenuated down to our upper limit the size of the corona has to be larger than 100 km and 130 km for a beaming and luminosity 1000 Hz oscillation. Clearly, this indicates that with the low optical depth derived for the Comptonizing cloud and for any plausible sizes of such a cloud, the attenuation is not very strong, and, if signal there is, it has to be intrinsically weak.

Another possibility that may explain the lack of HFQPOs in LS sources might be related to the position of the inner disk radius. Obviously, if the HFQPOs are generated in the disk and if the inner edge of the disk lies at large radius (see below), no signals at such high frequencies should be seen. In that respect, it is worth pointing out that the bump (around 10 Hz) in the PDS of 1E 1724−3045 (Fig. 6) was interpreted by Psaltis, Belloni, & Van der Klis (1999) as a low-frequency kilohertz QPO (the same bump is seen in GS 1826−238 and SLX 1735−269). Their conclusion was derived from the fact that the 0.8 Hz QPO and the bump at 10 Hz fitted in the global correlation observed over several frequency decades between $v_{\text{qpo}}$ and the frequency of the lower kilohertz QPOs (Psaltis et al. 1999).

4.2. Spectral Properties

To first order, the broadband LS spectra of NSs can be approximated with a PL followed by an exponential cutoff at 50−80 keV. There is also a weak soft component in two of
the three LS sources, with temperatures of \( \sim 0.5-1 \) keV contributing less than \( \sim 30\% \) of the total luminosity. The latter quantities when derived from the fit of PCA data are subject to uncertainties because the fit starts at 2.5 keV, because they depend on the \( N_{\text{H}} \) values assumed, and because there are some calibrations uncertainties of the PCA at low energies \( (E \lesssim 5 \) keV). However, as, for example, in the case of 1E 1724–3045, the values derived from our spectral fitting are consistent with the ones obtained from observations that are more sensitive to such a soft component (e.g., by BeppoSAX or ASCA: Guainazzi et al. 1998; Barret et al. 1999). Thermal Comptonization of these soft photons by hot electrons then appears to be the most plausible emission mechanism for these systems, and for a spherical scattering cloud the derived optical depths and electron temperatures are in the ranges \( 2 \lesssim \tau \lesssim 4 \) and \( 15 \lesssim kT_e \lesssim 30 \) keV. Thermal Comptonization also dominates the spectral formation in KS 1731–260, but with a significantly lower \( kT_e \) (\( \sim 3 \) keV) and larger \( \tau \) (\( \sim 10 \)). The main difference between a source in the HS and a source in the LS is best illustrated in Figure 12, where \( vFv \) plots of the PCA/HETE spectra of KS 1731–260 and GS 1826–238 are shown. Clearly, for KS 1731–260 the bulk of the energy is radiated below \( \sim 10 \) keV, whereas for GS 1826–238 the energy spectrum is flatter and a large fraction (\( \sim 50\% \)) of the energy is radiated in the hard X-ray band.

4.2.1. Iron Line Emission and Reflection in NS LMXBs

There is strong evidence for iron line emission in two of the three LS sources examined here (the evidence is weaker for 1E 1724–3045). The derived line energy is consistent with 6.4–6.5 keV, i.e., fluorescence from neutral/moderately ionized iron. There are three possible sites for line emission in LMXBs, the NS surface itself, the accretion disk, and accretion disk coronal wind. Any line from the NS would be strongly redshifted, down to \( \sim 5 \) keV, while the accretion disk corona should be strongly ionized, producing iron lines at 6.7 and 7.0 keV. Thus, the most likely origin for the observed 6.4 keV line is irradiation of the accretion disk by the X-ray source. If so, then it should be accompanied by a Compton reflected spectrum. We significantly detect a neutral reflected continuum in GS 1826–238 and a neutral/moderately ionized reflected continuum in SLX 1735–269.

The reflection albedo, the ratio between the reflected and incident luminosities, is then an observationally determined quantity from our data. The reflection probability is determined by the relative importance of electron scattering and photoelectric absorption. At low energies the X-ray photons tend to be photoelectrically absorbed rather than scattered, so the reflection probability is low, while at higher energies the opposite is true. The photoelectric absorption probabilities are determined by both the element abundances (more heavy elements mean more hard X-ray opacity and so less reflection) and ionization state (high-ionization states mean less bound electrons, so less opacity and more reflection). Beyond 10–20 keV, the photoelectric opacities become negligible in comparison to the electron scattering probability, but at these energies the electron scattering is not elastic. The incoming photons can lose much of their energy to the electrons as they scatter, leading to a marked decrease in the reflected probability above 50–100 keV. Thus, even high-energy photons can dump most of their energy in the disk. For hard spectra, such as those seen in GS 1826–238, the maximum albedo, even with complete ionization of the disk, is \( a_{\text{alb}} \sim 0.75 \), while the observed albedo is much less, \( \sim 0.25 \), because the ionization state of the reflecting material is low to moderate, so most of the low-energy incident flux is photoelectrically absorbed rather than reflected. For the HS spectra, such as KS 1731–260, the reflection albedo can be much higher if the disk is completely ionized, since the spectrum is much softer. This is important because the disk heating and hence optical/UV reprocessed X-ray flux is determined by the nonreflected flux, \( (1 - a_{\text{alb}}) \). Various attempts to derive the albedo from the optical reprocessed flux (e.g., de De Jong, van Paradijs, & Augusteijn 1996) give \( a_{\text{alb}} \sim 0.9 \). This is not in conflict with our values since most of the LMXBs considered were in the high state, where much more of the spectrum can be reflected. However, we caution that the optical determinations assume that the disk shape is given by Vrtilek et al. (1990), with height \( \propto r^{1/7} \). This was derived assuming that the disk is isothermal with height (central temperature equal to surface temperature), which is incorrect (e.g., Dubus et al. 1999).

While the fraction of incident to reflected flux depends on the X-ray albedo (which in turn is given by the elemental abundances and ionization state of the reflector and the spectral shape of the incident spectrum), the total amount of reflection seen depends on the solid angle subtended by the material, \( \Omega/2\pi = f_{\text{eff}} \), and its inclination to the line of sight. For an assumed inclination angle of \( 60\degree \), we derived \( f_{\text{eff}} \) = 0.15 and 0.28 in GS 1826–238 and SLX 1735–269, respectively, with associated iron line equivalent widths of 50 and 39 eV. The line equivalent widths and especially the reflected fractions are significantly lower than the \( \sim 130 \) eV and \( f_{\text{eff}} = 1 \) for an isotropic X-ray source above a flat, infinite disk (George & Fabian 1991; Matt, Perola, & Piro 1991).

4.2.2. Accretion Geometry

The broadband continuum spectrum, its variability (e.g., van der Klis 1994; Ford et al. 1999), and the properties of the reflected spectrum (Zycki, Done, & Smith 1998, 1999) are very similar to those seen in the LS BH systems, suggesting that the same physical mechanisms operate in a
similar accretion geometry. If so, then the hard emission cannot have anything to do with the magnetosphere or the NS surface and must instead be connected with the accretion flow. Mechanisms suggested for the hard power law in BH systems that can also work in NSs are an accretion disk corona (magnetic reconnection in flares above a disk) and a hot accretion flow. The lack of a strong reflection signature and weak soft emission is at first sight incompatible with the magnetic flaring model. A geometry where the hard X-ray source is above an optically thick disk should lead to \( f_{\text{soft}} \sim 1 \) rather than the \( f_{\text{soft}} \lesssim 0.3 \) observed here. In addition, of the hard X-ray flux, one-half will go up and escape while one-half will go down and illuminate the cool material. Of this, 10% can be reflected as a hard X-ray component (if the material is mostly neutral, and has solar abundances), but the remaining 90% is thermalized and should emerge as a soft component. The soft photon luminosity would then be roughly one-half that of the hard component. However, it is emitted only into a 2\( \pi \) solid angle because it is optically thick, and since the hard component is emitted into 4\( \pi \) the inferred luminosities of the soft and hard components should be about equal (see Gierlinski et al. 1997).

The properties of the reflected component and line emission together with the observation of time smearing or delays in the optical counterparts of X-ray bursts testify of the presence of an outer disk in those systems. It would seem however that a significant fraction of the disk cannot be seen in reflection, by reprocessing the hard X-ray radiation, or by emission. So the question is whether or not there is then an inner disk at all, say within \( \sim 50-100 R_\text{G} \). If not, then the disk corona model can be ruled out. However, the disk reflection and reprocessing signatures could perhaps be masked by a very highly ionized inner disk (Ross, Fabian, & Young 1998; but see Done & Zycki 1999), while the intrinsic disk emission is then cooler and less intense if the power is mostly dissipated in the corona (Svenssson & Zdziarski 1994). Another possibility is that the hot plasma has a bulk velocity \( \beta c \) directed away from the disk (Beloborodov 1999). The bulk motion might be due to the pressure of the reflected radiation and/or plasma ejection from magnetic flares. A mildly relativistic escaping flow (\( \beta \sim 0.3 \)) causes aberration that reduces the downward irradiating flux, which in turn reduces the feedback of reflection and reprocessing.

Perhaps the most telling discrepancy in all these models is that there should also be strong emission from a boundary layer where the disk and NS interact. The boundary layer emission can be twice as large as that from the accretion disk (whether standard disk or disk powered corona) once relativistic corrections are included (Sunyaev & Shakura 1986). There is no strong soft emission component in the spectrum, ruling out an optically thick boundary layer (unless it also dissipates most of the accretion energy in an optically thin region perhaps powered by magnetic reconnection). King & Lasota (1987) calculated that the boundary layer between a standard disk and the NS can be optically thin only for mass accretion rates much lower than those considered here (but see recent calculations by Inogamov & Sunyaev 1999; Popham & Sunyaev 2000, in preparation). Alternatively, if the disk is truncated at the last stable orbit (allowed only for certain NS equations of state) then the boundary layer is between material freely spiraling in rather than a disk. This can give an optically thin boundary layer up to luminosities of a few percent of Eddington, as required here (Kluzniak & Wilson 1991). However, it seems unlikely that an optically thin, hot boundary layer could be similar in temperature and variability to disk emission produced by a completely different process of magnetic flare. Removing the boundary layer by ejecting the material just before it reaches the NS surface (e.g., by a centrifugal magnetic field barrier or winds) is not a viable way around these difficulties. The observation of X-ray bursts from these systems proves that the accreting material does accumulate on the NS surface (e.g., GS 1826–238).

Such a series of requirements make the disk corona models seem rather contrived, so we investigate the alternative model, in which the inner disk is replaced by an X-ray-emitting hot flow. This would naturally account for the weakness of reflection and reprocessing and the relative weakness of the intrinsic soft emission. It also provides an explanation for the strong correlation observed between the relative strength of the reflection component (\( f_{\text{soft}} \)), and the photon index of the intrinsic PL (\( \Gamma \)) in Seyfert galaxies and Galactic BHs (Zdziarski et al. 1999). The same correlation also applies to NSs, including those considered here; for GS 1826–238, \( f_{\text{soft}} = 0.15\pm0.03 \), and \( \Gamma = 1.72\pm0.04 \), whereas for SLX 1735–269, the corresponding values are \( f_{\text{soft}} = 0.28\pm0.09 \) and \( \Gamma = 2.09\pm0.01 \). This correlation can be understood by considering a hot X-ray plasma that fills a variable-radius hole in the inner disk: as the disk radius decreases, its solid angle increases, thereby increasing both the reflection and the flux of cool cooling photons. The stronger cooling of the hot plasma then leads to a steepening of the PL slope (Zycki et al. 1998; Zdziarski et al. 1999).

The above scenario, in which the innermost radius of the accretion disk moves as a function of spectral state, can also naturally explain the strong correlation between spectral properties and the frequency of the HFQPOs (e.g., Kaaret et al. 1998; Mendez et al. 1999; Bloser et al. 2000). While there are several current models proposed for these high-frequency features in the power spectrum, they all require that the NS spin beats with an inner disk frequency (see e.g., the review by Van der Klis 1998). The easiest way to change the inner disk frequency is to change the inner disk radius. This then naturally explains the lack of HFQPOs in the LS NSs as due to the NS being a system in which the inner disk is truncated at large radii, where the interaction with the NS surface is small. As the disk moves inward, the spectrum softens (\( \Gamma \) increases, e.g., in 4U 0614+09 and 4U 1608–52 [Kaaret et al. 1998], and the disk contribution increases, e.g., in 4U 0614+09 [Ford et al. 1997]), the HFQPOs appear, and their frequencies increase (Piraino et al. 1999).

How can we reconcile our spectral and timing observations in that picture? GS 1826–238 would have an accretion disk with a large inner radius. Its inner disk temperature is then too low for its contribution to be detected with the PCA. The cooling is low, its spectrum is hard, and the amount of reflection is rather small. Con-

---

8 Alternatively, this correlation can also be explained by the outflow model of Beloborodov (1999). Increasing the semirelativistic outflow velocity, \( \beta \), leads to a decrease of both \( \Gamma \) and \( f_{\text{soft}} \), and yields a correlation that seems to fit better the observations than the two phase disk model (Zdziarski et al. 1999). Another interesting feature of the ejection model is that it can explain \( f_{\text{soft}} \gtrsim 1 \) (as observed in some Seyfert galaxies) because for negative values of \( \beta \) the coupling between the ejected plasma and the disk can be very strong. As said above, however, the weak point of such a model is that it relies on the poorly known physics of the magnetic dissipation within the disk.
versely, for SLX 1735 − 269, the disk extends closer to the irradiating source, the solid angle for reflection is larger and its spectrum is softer. Finally for KS 1731 − 260, the disk gets even closer; kilohertz QPOs are produced and are seen before disappearing as a response to a further increase of the accretion rate. The cooling is strong and leads to a quenching of the hard X-ray emission; at the same time the iron line gets stronger (so, probably, does the reflection component). The above picture, although attractive, does not explain why 1E 1724 − 3045, which has spectral and timing parameters more or less similar to SLX 1735 − 269, does not display a reflection component (yet it shows a weak iron line). One possible explanation could be that the inclination is larger for 1E 1724 − 3045 than for SLX 1735 − 269.

4.2.3. Emission Mechanisms

What can replace the inner accretion disk? The recent rediscovery of a stable, X-ray hot solution of the accretion flow equations has caused much excitement. The main assumptions of these advective solutions are that the gravitational energy released by viscosity is gained mainly by the protons and that these heat the electrons only by Coulomb collisions. For low mass accretion rates the flow is optically thin so that the Coulomb collision rate is very low. The proton temperature is high, so the flow has a large scale height (quasi-spherical). The small amount of energy that is gained by the electrons is radiated as cyclo/synchrotron emission, bremsstrahlung and Comptonization of these seed photon distributions (Narayan & Yi 1995). A pure advective model has a disk existing only at very large radii, where its emission is negligible. The resulting spectrum is then rather hard, since the only seed photons are the self-produced ones in the optically thin flow and the electron temperature is of order \( \sim 100 \text{ keV} \) (Narayan & Yi 1995). As the mass accretion rate increases, the flow becomes denser, so the Coulomb collisions are more effective at transferring energy from the protons to the electrons, so the radiative efficiency increases. However, this process cannot continue indefinitely: as the flow becomes optically thick, the Coulomb collisions drain all the energy from the protons and the flow collapses into a standard, optically thick, geometrically thin accretion disk (Esin et al. 1998).

However, there is a clear difference between advective models for BH and NS systems. For BHs the energy advected with the protons in the flow can be swept invisibly down into the black hole. Such a flow will collapse at \( L \sim 0.4 z^2 L_{\text{Edd}} \), where \( z \sim 0.2 \) (Yi et al. 1996) is the disk viscosity. For NSs the advected energy is released in a boundary layer as the flow hits the NS surface. If this boundary layer is optically thick, then the increase in seed photons for the Compton cooling will cause the advective flow to collapse at Eddington scaled mass accretion rates lower (by at least a factor 3) than for BHs (Narayan & Yi 1995; Yi et al. 1996). Yet the spectral state transition takes place at roughly the same Eddington fraction for NSs and BHs, namely, at \( \sim 0.05 \)–\( 0.1 L_{\text{Edd}} \) (see, e.g., Mitsuda et al. 1989 for the NS 4U 1608 − 52; Esin, McClintock, & Narayan 1997, Esin et al. 1998 for the BH Cyg X-1), and no strong soft emission from a boundary layer is seen.

One way out of this impasse is if the boundary layer is optically thin. Explicit calculations for the boundary layer between an ADAF and the NS surface have not yet been done, though rather different spherical flows have been shown to give optically thin boundary layer emission up to fairly high luminosities (e.g., Zane, Turrolla, & Treves 1998). Thus an optically thin boundary layer between an advective flow and NS seems plausible. In this case, the boundary layer is an additional heating source for the hot plasma in the advective flow, so it might be expected to merge rather smoothly in both spectral and variability properties with the rest of the hot, optically thin accretion flow. The extra photons from the boundary layer are then hard. This lowers the temperature of the advective flow slightly, but the critical mass accretion rate that can be sustained in the flow is then very similar to that calculated for the BH case (Narayan & Yi 1995). The one caveat to this is that even if the boundary layer were optically thin then the NS surface would intercept and thermalize some of the boundary layer emission, again leading to an additional source of soft seed photons. If the NS surface is ionized and/or mainly made up of hydrogen because of settling of heavy elements, then the reflection albedo can be as high as 0.6. Thus at least 25% of the boundary layer luminosity should emerge as a soft component. We are currently calculating the effect of such an optically thin boundary layer plus its thermalized emission on the properties of the advective accretion flow, to see whether it can allow the observed similarity in state transition accretion rate between BHs and NSs.

It has been recently suggested that mass loss via winds is a natural consequence of ADAFs and is such that only a tiny fraction (\( < 1 \)) of the gas supplied through the ADAFs is actually accreted onto the central object (Blandford & Begelman 1999; Quataert & Narayan 1999). Such winds would provide an alternative explanation for the dimness of quiescent BHs, attributed in the ADAF models, to low radiative efficiency and the existence of event horizons in those systems (Narayan, Garcia, & McClintock 1997; Menou et al. 1999). However, in our picture, in which the NS is surrounded by an ADAF, the observation of X-ray bursts tells us that all the matter flowing through the ADAF can be accreted onto the NS, so, unless the mass transfer rate is very much larger than currently thought in LMXBs (see Menou et al. 1999 for a recent discussion), the presence of ADAFs around bursting NSs would strongly argue against the existence of powerful winds from such accretion flows (i.e., ADIOS in Blandford & Begelman 1999).

To summarize, the similarity of the BH and NS spectra and variability in their LS strongly suggest that the same mechanisms are operating, i.e., that the hard X-ray emission is connected to the accretion flow with the NS surface having little impact on it. Although the latter remains an unescapable part of the system, there is nothing that can be firmly associated with the strong emission expected from the surface or the boundary layer even though it is known that the accretion material has to accumulate onto the NS surface because of X-ray bursts. This problem applies to both the disk corona and advective flow models. The boundary layer emission then must either be optically thin or be emitted at too low a temperature to be observed. The latter seems unlikely given previous ASCA and BeppoSax observations; hence we conclude that the boundary layer is optically thin and hot (see recent calculations by Popham & Sunyaev 2000, in preparation; Inogamov & Sunyaev 1999). However, it seems difficult to imagine a situation in which the boundary layer emission could have similar spectral and variability properties to magnetic flares above a disk. Hence we favor models in which the inner disk is replaced by an
X-ray hot, optically thin flow. The only known stable hot solutions to the accretion equations are the advective flows. Unfortunately ADAF solutions have not been developed with self-consistency for the NS case, and it is not yet known whether these can have an optically thin boundary layer. If so then this emission could well merge smoothly with the hot optically thin advective flow. We stress that the maximum mass accretion rate at which an advective flow can be sustained holds out the possibility of showing whether or not advective flows can really be present. Observations show that the hard/soft spectral transition associated in these models with the collapse of the advective flow occurs at roughly the same mass accretion rate in both NS and BH systems. While an optically thick boundary layer produces a large difference in this critical mass accretion rate, an optically thin boundary layer does not. However, even an optically thin boundary layer produces some soft photon flux from reprocessing of the flux illuminating the NS surface, which will lower this critical mass accretion rate. Further calculations are needed to see whether this effect is small enough to match the observed spectral transitions in NSs.

4.3. Comparison between BHs and NSs

Thanks to RXTE and BeppoSax, the number of LS NSs observed simultaneously in X-rays and hard X-rays is growing rapidly, so reliable comparisons between BHs and NSs can now be carried out. Although, as illustrated in this paper, the most recent data indicate that BHs and NSs are very similar in many respects, especially in their low states, it remains critical to search for observational criteria that could distinguish these two types of accreting systems.

4.3.1. Spectral Shape Differences?

Heindl & Smith (1998) have pointed out that the index of the power-law part of the spectrum is significantly larger for NSs than for BHCs ($\Gamma \gtrsim 1.8$ for NSs versus $1.4 \lesssim \Gamma \lesssim 1.6$ for BHs; see, however, Churazov et al. 1997 for an opposite conclusion). The data presented here are in general terms consistent with this claim but indicate that the separation is by no means large (the index for GS 1826–238 is 1.7). On the other hand, Heindl & Smith’s claim is inconsistent with several recent observations of NSs, such as, for example, those of SAX J1748.9–2021 in NGC 6440 (In’t Zand et al. 1999) or those of the two dippers 4U 1915–05 (Church et al. 1998) and XB 1323–619 (Balucinska-Church et al. 1999). In the first case, a fit by a broken PL yields a photon index of 1.54 ± 0.03 and 2.13 ± 0.04 below and above the break at 18.1 ± 1.2 keV (In’t Zand et al. 1999). For 4U 1915–05, the broadband 0.2–200 keV nondip BeppoSax spectrum can be fitted by a blackbody plus a cutoff PL of index 1.6 ± 0.01 ($E_{\text{cutoff}} = 80.4 \pm 10$ keV). Similarly, for XB 1323–619, Balucinska-Church et al. (1999) have found that the nondip spectrum is a cutoff power law with $\Gamma = 1.48 \pm 0.01$ and $E_{\text{cutoff}} = 44.1$ keV. Based on these observations, we therefore conclude that the above criterion is not valid.

It has also been proposed that, in the framework of thermal Comptonization models, the electron temperature of the scattering cloud ($kT_e$) appears to be systematically lower for NSs than for BHs: $kT_e \lesssim 30$ keV versus $kT_e \gtrsim 50$ keV (Tavani & Barret 1997; Zdziarski et al. 1998; Churazov et al. 1997). This naturally reflects the standard picture that, on average, BH spectra are harder than NS spectra and has been tentatively explained by the additional cooling provided by the NS surface, which may act as a thermostat capable of limiting the maximum $kT_e$ achievable in these systems (Kluzniak 1993; Sunyaev & Titarchuk 1989). The data presented in this paper are certainly consistent with this criterion. However, it is worth noting that there are some speculative BHCs (e.g., GRS 1758–258) for which $kT_e$ derived from the fitting of their hard X-ray spectra with the Sunyaev & Titarchuk (1980) Comptonization model (COMPST in XSPEC) is below 50 keV ($kT_e \sim 33$ keV in Mandrou et al. 1994 from a fit of SIGMA data alone). However, as pointed out by Zdziarski et al. (1998), the latter temperature is probably a gross underestimate and should be reevaluated using broadband spectra and more appropriate relativistic Comptonization models including Compton reflection and relativistic effects (e.g., Poutanen & Svensson 1996). If such an underestimate has indeed been observed in Cyg X-1 ($kT_e$ increased from 27 keV with COMPST up to $\sim 100$ keV with COMPPS; Gierlinski et al. 1997), we note that in the case of 1E 1724–3045, $kT_e$ derived with COMPTT is 30 keV, whereas it is only slightly larger ($\sim 35$ keV) with the relativistic COMPPS model (the same is true for GS 1826–238). Bearing this in mind, it remains that this criterion should be considered seriously for sources showing evidence for thermal cutoffs in their hard spectra. More data should tell us soon whether all BHCs fitted with relativistic Comptonization models will indeed have $kT_e \gtrsim 50$ keV, whereas all NSs fitted with the same models will have $kT_e$ below the above value.

In any case, the above criterion applies when an energy cutoff is observed. However such cutoffs are not always present in NS hard X-ray spectra. The first SIGMA observation of 1E 1724–3045 revealed a nonattenuated hard power law ($\Gamma = 1.8$) extending up to 200 keV (Barret et al. 1991). Aql X-1 was also observed by BATSE from 20 keV up to $\sim 100$ keV with $\Gamma$ in the range 2.1–2.6 and no evidence for a high-energy cutoff (Harmon et al. 1996). Finally, a recent BeppoSax observation of 4U 0614+09 has placed a lower bound on any exponential cutoff of the power law ($\Gamma = 2.3$) of 200 keV9 (Piraino et al. 1999). This means that, just as there are two classes of BHs based on their hard X-ray spectra (Grove et al. 1998), there might also be two classes of NSs. Members of the first class would display hard X-ray spectra with energy cutoffs, which would result from thermal Comptonization. Members of the second class would have nonattenuated power laws (up to an energy that remains to be accurately determined), similar to the power laws observed in the soft state of BHs. Such power laws could be produced by nonthermal Comptonization, i.e., Comptonization on nonthermal particles (for recent reviews see Poutanen 1999; Coppi 1999). Alternatively, Titarchuk, Mastichiadis, & Kylafis (1997) have proposed that these power laws could be produced by bulk Comptonization in a convergent accretion flow. The same mechanism seems to

9 Alternatively, the BeppoSax spectrum could be modeled as thermal Comptonization (COMPPS model in XSPEC; Poutanen & Svensson 1996) for which a very high $kT_e$ was derived (246 ± 56 keV; Piraino et al. 1999). Such a value, which puts the cutoff energy above 700 keV, is itself well above the high-energy threshold of the BeppoSax/PDS (the last significant data point of the spectrum is at 180 keV) and therefore must be considered with caution. However, if this result is confirmed by observations performed at even higher energies, it would make the $kT_e$ criterion discussed above definitively invalid.
be ruled out for NSs because it produces spectra much harder than that observed ($\Gamma \lesssim 1$; Titarchuk, Mastichiadis, & Kylafis 1996). BHs with power laws have typical $\Gamma$ in the range 2.5–3.0, or similar to NSs in the hard X-ray band (e.g., 1E 1724–3045). Therefore, the indication of a steep hard X-ray spectrum ($E \gtrsim 30$ keV) spectrum with $\Gamma \gtrsim 2.5$ cannot alone be used to claim that an unknown system contains a NS. Similarly, a hard X-ray power-law spectrum with $\Gamma \lesssim 2.5$ is not unique to BHs (e.g., 4U 0614+091).

4.3.2. Luminosity Differences?

The idea that BHs and NSs are actually hardly distinguishable by their broadband spectral shape has led Barret et al. (1996) to propose a luminosity criterion (see also Barret & Vedrenne 1994; Van Paradijs & Van der Klis 1994). They compared the 1–20 keV luminosity ($L_{1-20}$) to the 20–200 keV luminosity ($L_{20-200}$) for all secure BHBs (by “secure,” we mean BHs with mass function estimates indicating a compact object of mass larger than $3M_\odot$), hereafter BHBs for BH Binaries), and all NSs detected up to at least 100 keV. Figure 13 is an updated version of Figure 1 in Barret et al. (1996). There are now 16 NSs detected at 100 keV with (quasi-) simultaneous coverage (by “secure,” we mean BHs with mass function estimates indicating a compact object of mass larger than $3M_\odot$), hereafter BHBs for BH Binaries), and all NSs detected up to at least 100 keV. Figure 13 is an updated version of Figure 1 in Barret et al. (1996). There are now 16 NSs detected at 100 keV with (quasi-) simultaneous coverage in X-rays; all but the Cen X-4 detections came within the last 8 yr. This figure includes six more NSs recently detected by either RXTE (PCA + HEXTE) or BeppoSax (MECS + LECS + HPGSPC + PDS), namely, the millisecond pulsar SAX J1808.4–3658 (Gilfanov et al. 1998; Heindl & Smith 1998), the dippers 4U 1915–05 (Church et al. 1998) and XB 1323–619 (Balucinska-Church et al. 1999), SAX J1748.8–2021 (In’t Zand et al. 1999), SLX 1735–269, and GS 1826–238 (this work). For the two dippers, $L_{1-20}$ and $L_{20-200}$ have been computed from their nondip spectra. In addition, the luminosities for 1E 1724–3045 (this work), for 4U 0614+091 (BeppoSax observation; Piraino et al. 1999), and Aql X-1 (joint nearly simultaneous BATSE and ASCA observations; Rubin et al. 2000) have been updated. The figure also includes GRS 1009–45 (Nova Velorum 1993), recently shown to be another secure BHB (Filippenko et al. 1999).

For SAX J1808.4–3658 and 4U 1915–05, we have assumed the distances inferred from X-ray burst studies, 4 and 9.3 kpc, respectively (In’t Zand et al. 1998; Yoshida 1992), and for XB 1323–619 we have assumed a distance of 10 kpc (Balucinska-Church et al. 1999). SAX J1748.8–2021 is located in the globular cluster NGC 6440, whose distance is estimated to be $8.5 \pm 0.5$ kpc (Ortolani, Barbuy, & Bica 1994). For GRS 1009–45 we have estimated the distance according to the method described in Barret et al. (1996). We determine the radius of the secondary assuming that its Roche lobe (the radius is then given by the orbital period $P_{\text{orb}} = 6.86$ hr, and its mass, which we take to be $0.5 M_\odot$). For a K7 secondary, from the absolute visual flux, we determine the absolute visual magnitude $M_V \sim 8.2$, according to the values tabulated by Popper (1980). Finally, using the apparent dereddened magnitude corrected for interstellar reddening and for the contribution by the accretion disk to the continuum flux ($V_{\text{quint}} = 21.4–21.9$, $E(B-V) = 0.2$, $f_{\text{disk}} = 60\%$; Shahbaz & Kuulkers 1998), we obtain a distance in the range 5.0–6.5 kpc. Shahbaz & Kuulkers (1998) using an empirical linear relationship between the orbital period, the optical outburst amplitude magnitude derived a distance of 4 kpc. We adopt in Figure 13 a distance of 5 kpc. The X-ray and hard X-ray fluxes for

![Figure 13](image-url)

**Fig. 13.**—Hard X-ray (20–200 keV) vs. X-ray (1–20 keV) luminosities of black hole binaries (filled symbols) and neutron star binaries (open symbols). Only BHs with mass functions indicating compact object masses in excess of $3M_\odot$ are considered. For NSs, the luminosities are computed from observations in which the source was detected up to at least 100 keV. For KS 1731–260, the luminosities drawn correspond to the SIGMA detection (Barret et al. 1992). This is an updated version of Fig. 1 in Barret et al. (1996), from which most luminosities can be retrieved. The so-called X-ray burster box is plotted as a dot-dashed line. Its boundaries are simply defined to contain all the NSs.
GRS 1009–45 have been taken from Barret et al. (1996) from observations reported by Sunyaev et al. (1994).

Looking at Figure 13, one can see that the distinction in luminosity clearly holds: all NSs lie in the so-called X-ray burster box, whereas all BHs are found outside it. This figure shows that comparisons of $L_{20-200\,\text{keV}}$ and $L_{1-20\,\text{keV}}$ can be used to distinguish between BHs and NSs. First, although the presence of a hard tail is not a unique signature of BH accretion, the high luminosity in the hard tail appears to be such a signature: only BHBs are observed with where we define $L_{\text{crit}}$ to be unable to achieve electron temperature as high as BHs, and hence Comptonization with $kT_e > 50$ keV would be a BH signature. This criterion is weakened, however, by the fact that there are some NSs that do no display high-energy cutoffs in their hard X-ray spectra. The second is a luminosity-based argument and claims that only BHs are capable of emitting bright hard X-ray tails with luminosities larger than $\sim 1.5 \times 10^{37}$ ergs s$^{-1}$.

The RXTE archive contains a wealth of observations of NSs and BHs in different luminosity states and represents a very uniform data set that should be used to test the picture proposed in this paper. It is also clear that the same data can be used to challenge the observational criteria discussed above to distinguish BHs from NSs.

This research has made use of data obtained through the High-Energy Astrophysics Science Archive Research Center, operated by the NASA Goddard Space Flight Center. G. K. S. is grateful to CESR for its hospitality during the period of this work. D. B. wishes to thank the organizers of the 1999 ITP Black Hole Program (R. Blandford, D. Eardley, and J. P. Lasota) and the participants (R. Taam, S. Kato, A. Zdziarski, P. Coppi, and O. Blaes) for providing us with the PCA calibration uncertainties at low energies, we have detected a Compton reflected component plus an iron Kα line in two systems. In both cases, the data indicate that the most likely site for the reflector is a cool accretion disk, which is truncated somewhere to offer a relatively small solid angle to the irradiating source, which could be a quasi-spherical hot advection dominated inner accretion flow. Similar behavior is observed among BHs leading to very similar conclusions. In addition, within the limitations of the PCA calibration uncertainties at low energies, we have detected a soft component, which is equally well described by a multicolor disk blackbody or a blackbody. In our picture, this soft component most probably originates from the truncated accretion disk.

At higher energies, the HEXTLE sensitivity is sufficient to accurately locate the energy cutoff in the low-state hard X-ray spectra of these systems. When combined with PCA data, we have shown that the spectral steepness of the hard tails observed by SIGMA/BATSE was not intrinsic but rather was due to the presence of a high-energy cutoff ($\sim 50-80$ keV). The cutoff power-law spectral shape observed strongly suggests that thermal Comptonization is the dominant emission mechanism in these systems. The Comptonization process would take place in an optically thin hot boundary layer merged with the central advective corona, located between the truncated accretion disk and the NS surface.

Of the most recent criteria that have been proposed to distinguish BHs from NSs (out of quiescence), two appear consistent with all the available data. The first one states that for NSs displaying thermal Comptonization, they seem to be unable to achieve electron temperature as high as BHs, and hence Comptonization with $kT_e > 50$ keV would be a BH signature. This criterion is weakened, however, by the fact that there are some NSs that do no display high-energy cutoffs in their hard X-ray spectra. The second is a luminosity-based argument and claims that only BHs are capable of emitting bright hard X-ray tails with luminosities larger than $\sim 1.5 \times 10^{37}$ ergs s$^{-1}$.

5. SUMMARY

We have reported RXTE timing and spectral observations of four type I X-ray bursters. The results presented here nicely illustrate that, in addition to its unprecedented timing capabilities, RXTE has also sufficient sensitivity for detailed spectral studies. Our spectral fitting has revealed that the broadband spectra of low-state NSs are often more complicated than previously thought. In particular, we have detected a Compton reflected component plus an iron Kα line in two systems. In both cases, the data indicate that the most likely site for the reflector is a cool accretion disk, which is truncated somewhere to offer a relatively small solid angle to the irradiating source, which could be a quasi-spherical hot advection dominated inner accretion flow. Similar behavior is observed among BHs leading to very similar conclusions. In addition, within the limitations of the PCA calibration uncertainties at low energies, we have detected a soft component, which is equally well described by a multicolor disk blackbody or a blackbody. In our picture, this soft component most probably originates from the truncated accretion disk.

At higher energies, the HEXTE sensitivity is sufficient to accurately locate the energy cutoff in the low-state hard X-ray spectra of these systems. When combined with PCA data, we have shown that the spectral steepness of the hard tails observed by SIGMA/BATSE was not intrinsic but rather was due to the presence of a high-energy cutoff ($\sim 50-80$ keV). The cutoff power-law spectral shape observed strongly suggests that thermal Comptonization is the dominant emission mechanism in these systems. The Comptonization process would take place in an optically thin hot boundary layer merged with the central advective corona, located between the truncated accretion disk and the NS surface.

Of the most recent criteria that have been proposed to distinguish BHs from NSs (out of quiescence), two appear consistent with all the available data. The first one states that for NSs displaying thermal Comptonization, they seem to be unable to achieve electron temperature as high as BHs, and hence Comptonization with $kT_e > 50$ keV would be a BH signature. This criterion is weakened, however, by the fact that there are some NSs that do no display high-energy cutoffs in their hard X-ray spectra. The second is a luminosity-based argument and claims that only BHs are capable of emitting bright hard X-ray tails with luminosities larger than $\sim 1.5 \times 10^{37}$ ergs s$^{-1}$.

The RXTE archive contains a wealth of observations of NSs and BHs in different luminosity states and represents a very uniform data set that should be used to test the picture proposed in this paper. It is also clear that the same data can be used to challenge the observational criteria discussed above to distinguish BHs from NSs.

This research has made use of data obtained through the High-Energy Astrophysics Science Archive Research Center, operated by the NASA Goddard Space Flight Center. G. K. S. is grateful to CESR for its hospitality during the period of this work. D. B. wishes to thank the organizers of the 1999 ITP Black Hole Program (R. Blandford, D. Eardley, and J. P. Lasota) and the participants (R. Taam, S. Kato, A. Zdziarski, P. Coppi, and O. Blaes) and for their hospitality at the Institute of Theoretical Physics, where part of this work was completed. D. B. acknowledges many exciting discussions with all of them. This research was thus supported in part by the National Science Foundation under grant PHY94–07194. D. B. also thanks the organizers of the Aspen Center for Physics summer workshop on X-Ray Probes of Relativistic Effects near Neutron Stars and Black Holes (J. E. Grindlay, P. Kaaret, W. Kluzniak, F. Lamb, M. Nowak, and W. Zhang) for inviting him and for their hospitality during the workshop.

The authors are grateful to J. Swank and K. Jahoda for discussions about the PCA calibrations, to L. Titarchuk for useful discussions during his stay at CESR, to A. Zdziarski for providing us with the Ginga spectrum of GS 1826–238, to J. Poutanen for the supply of his relativistic Comptonization model (COMPPS), and finally to P. Kaaret for sending us in advance a copy of the paper Piraino et al. (1999) on 4U 0614+09.

This paper greatly benefited from many useful comments by A. Bazzano, P. F. Bloser, E. C. Ford, M. Guainazzi, P. Kaaret, W. Kluzniak, J. P. Lasota, J. E. McClintock, J. Poutanen, R. Taam, M. Van der Klis, A. Zdziarski, S. N. Zhang, and W. Zhang.

Finally, we are thankful to Dimitrios Psaltis, the referee, for many insightful and thoughtful comments on this paper.
