NS-LMXBs in Low-Hard State: evidence for two spectral substates

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abstract

This work updates (and confirms) the preliminary results already presented in Cocchi (2011): an accurate screening of the *BeppoSAX* archive showed how the Low Hard State (LHS) spectra of Neutron Star (NS) Low-Mass X-ray Binaries (LMXB) can be divided in two main subclasses:

- *canonical* LHS spectra with two well separated soft photon populations (disk and NS) and
- spectra where only a single soft population (likely associated to the inner disk) is detected.

The archive screening is still in progress and, to date, the analysed sample includes **36** NS-LMXBs in **59** pointed observations. A total of **21 sources** (in **32 observations**) exhibited LHS spectra.

About half (18) of the LHS observations displayed a *canonical* LHS spectrum, in which two well separated populations of soft blackbody-distributed photons emerge (**2-P** spectra). One, or possibly both the populations, is Comptonized by a hot (kTe > 15 keV) electron plasma cloud.

For the remaining (14) observations just a single population is sufficient to account for both the directly observed blackbody and the Comptonized (kTe > 20 keV) radiation (**1-P** spectra).

The luminosities of the canonical 2-P spectra are found to be systematically higher than those of the 1-P spectra. This strongly suggests a simple physical explanation for this dichotomy observed in NS-LMXB LHS spectra: the transition from the lower-luminosity 1-P subclass to the 2-P one is likely related to increasing accretion rate, which drives the presence of a hotter X-ray photon population in the close vicinity of the NS, or possibly a stronger thermal gradient in the inner, X-ray active, accretion disk.

The 1-P spectra are the ones preferably emitted by (candidate) Ultra-compact (UCX) binary systems. This is not unexpected, as UCX candidates are selected mainly because of their low persistent luminosity. Besides that, being 1-P spectra associated to the lowest luminosities, in this substate the electron coronal temperature is expected to be the highest because of the absence (or inefficiency) of the Compton cooling. This is confirmed by the kTe temperatures of the 1-P spectra in the analysed sample.

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The NS-LMXB spectra

Neutron Stars (NS) in Low Mass X-ray Binaries (LMXBs) are typically observed in two main spectral states: a bright High/Soft State (HSS) and a (fainter) Low/Hard State (LHS).

Both HSS and LHS spectra are generally described by two (main) components: a Comptonized radiation of soft seed photons, dominating the high energy output, and a soft, blackbody-like, emission, detected at lower energies (E < 5 keV).

The temperature of the Comptonizing electron plasma is very different in the two states (2-4 keV in HSS and 15-25 keV in LHS) and characterizes the wide band spectral shape: a bright soft X-ray bump with no or poor high energy emission in HSS; a small soft bump and evident hard-X extension (up to 200 keV) in LHS.

Effective Compton cooling associated to higher luminosities is able to explain the much lower coronal temperatures observed in the HSS.

As the temperature of the blackbody component is generally different from the one of the Compton-modified seed photons, both the states are characterised by two well separated, blackbody-like, soft X-ray photon populations. Depending on the temperatures of these populations, two classical models properly fit the data: the *Eastern model* (Mitsuda et al., 1988), with a cold (kT = 0.3-0.6 keV), disk-like, directly observed photon population and hotter (kT = 1-2 keV) Comptonized population; and the *Western model* (White et al. 1988), with hot, NS originating, blackbody and colder Comptonized seed photons.

At least for LHS spectra, Eastern-like models look preferable (e.g. Guainazzi et al., 1998, for a BeppoSAX application) also because this kind of models deal with very compact X-ray emitting regions, which is required by the quick variability of NS-LMXBs. Up to now, the multicolour nature of the directly observed blackbody is not unambiguously confirmed by the wide band data, as pure blackbody is also sufficient to model the disk photon population.

Evidence for a new subclass of LHS spectra was recently reported (Cocchi, 2011). These spectra are typically observed at the lowest luminosities (1-5x10^36 erg/s) and display a single (probably disk-originated) population accounting for both the directly observed blackbody-like radiation and the Comptonized one (1-P substates). Canonical two-population (2-P) LHS spectra seem to be associated to higher luminosities (about 10^37 erg/s).

The *BeppoSAX* NS sample, and a unifying idea

The *BeppoSAX* observatory was particularly suited for wide-band, high-sensitivity studies of NS-LMXBs, and able to accurately characterise both the soft photon populations and the electron coronae properties in an unbiased manner. Its on-line archive at the ASI Science Data Centre (ASDC) provides standard analysis products (spectra, lightcurves) for each performed observation (http://www.asdc.asi.it/bepposax).

Joint MECS, LECS and PDS spectra, deconvolved by the officially released BeppoSAX response matrices and ancillary files, can be thus analysed; for this work, the XSPEC fitting tool (version 12) was used. HPGSPC spectra are generally not available as ASDC products, so they are not considered for this preliminary BeppoSAX overview of NS-LMXBs.

In this investigation all the available NS-LMXBs are considered, regardless of the "zoological families" they are associated to: persistent emitters, transients, globular cluster sources (GCS), X-ray bursters, atolls, Z, GX sources, dippers, ultra compact binaries (UCXB), etc. Though this may seem risky, the idea is to avoid any pre-existing, conceptual, bias.

Indeed, as this work is focused on the broadband properties of LHS spectra a unifying, zero-order idea can be: the mass of the NS characterizes the potential well and the very inner, final disk accretion regions (the last 100 km, where X-rays are produced). As the NS masses (and so the final accretion geometries) are not expected to be broadly distributed, one can assume, to a first approximation, that the trends of the main observed spectral characteristics are fairly general.

Rough and naive as this assumption can seem, here it demonstrates its own practical usefulness.

The LHS subclasses

To date, the analysed sample includes **21** NS-LMXBs in LHS (totalling **32** observations).
The conclusions in Cocchi (2011) are confirmed. In particular, two kind of LHS spectra can be distinguished:

1) Canonical Two-population LHS spectra (**2-P**). Found in **18** observations.
Two blackbody (or multicolour) populations are actually needed to effectively describe the spectra.
The colder population (colour temperatures in the range 0.3-0.6 keV) is likely associated to the (inner) accretion disk and is likely multicolour in its nature, even though an ideal blackbody fits to the data equally well. The hot photon population (kT in the 1-2 keV range), which is the one Comptonized by the electron corona (*Eastern*-like model, see Mitsuda, 1989) should be centrally located, connected to a boundary layer (BL) or the NS itself.
The coronal temperatures are in the 15-25 keV range.

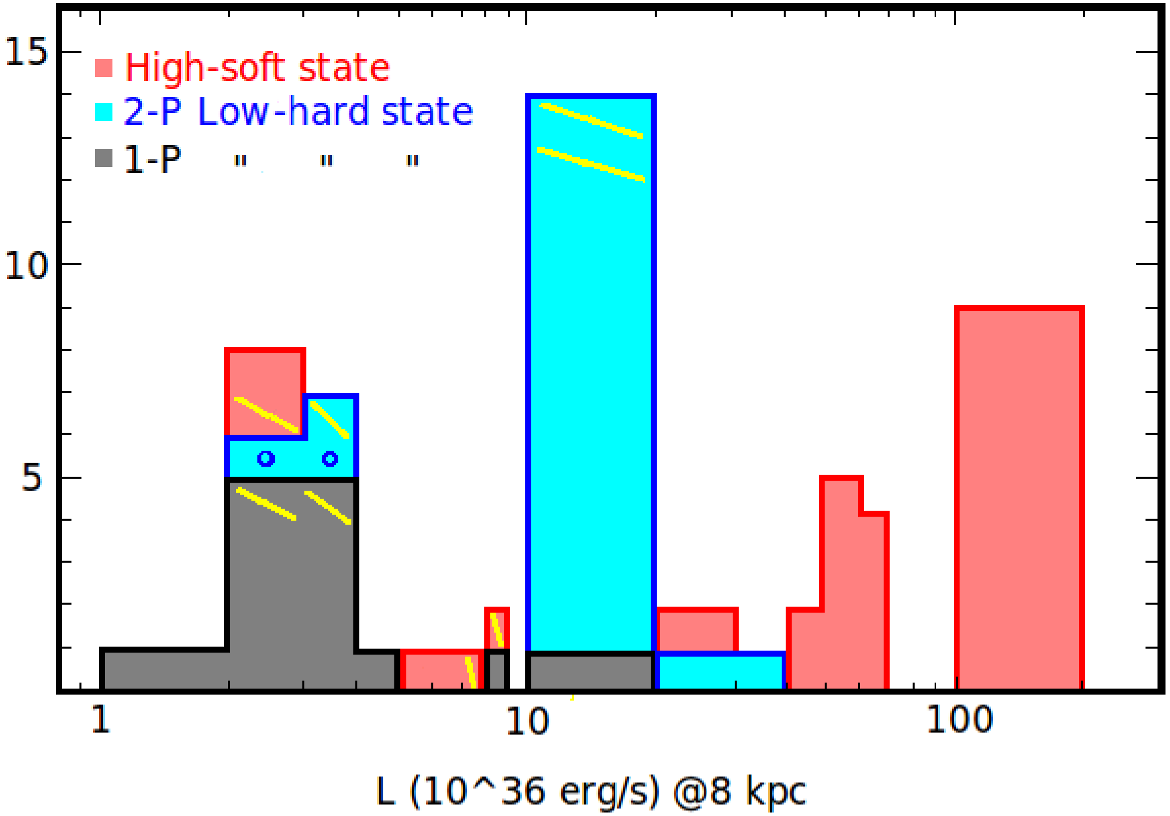
2) Single population LHS spectra (**1-P**). Found in **14** observations.
A single soft (disk, kT < 1 keV) population is sufficient in providing both the directly observed blackbody-like radiation (likely multicolour even though ideal blackbody is always acceptable) and the seed photons for the high energy Comptonized emission.
The electron plasma temperatures are slightly higher than in the 2-P spectra, in the 20-30 keV range.

The spectral models

In this analysis, Comptonization was effectively modeled by e.g., *compTT* (Titarchuk, 1994), *compTB* (Farinelli et al., 2008) or *nthcomp* (Zdzizrski et al., 1996; Zycki et al., 1999). In particular, *nthcomp* (via its `input_type` parameter) was applied to test multicolour disk photons as seed population for the Comptonizing electron corona.
Interstellar H absorption, modeled by *wabs* in XSPEC 12, was also included.

The Xspec formulas typically applied to fit the 1-P spectra were:
– **`wabs*(diskbb+nthcomp)`** with multicolour disk input for nthcomp (`input_type` = 1, effective in testing disk geometries) and tied inner `diskbb` and seed photon temperatures (one population)
– **`wabs*compTB`**, used in a thermal fashion (no bulk contribution) and with directly emerging blackbody radiation (this is a single population model by definition).
In general, pure blackbody or multicolour models are equally effective.

For 2-P spectra, the formulas were:
– **`wabs*(diskbb+nthcomp)`** with pure blackbody input for nthcomp (`input_type` = 0)
– **`wabs*(blackbodyrad+compTB)`** with compTB used in fully thermal mode, similar to CompTT (no bulk contribution, no directly observed blackbody, see e.g. Cocchi et al., 2011).
Again, the multicolour nature of the soft photon population could not be constrained.
In agreement with Cocchi et al. (2011), also a model assuming both the soft populations to be Comptonized by the same electron cloud well fits to the BeppoSAX data, and in some cases seems to be slightly preferable. This model was implemented in XSPEC by **`wabs*(compTB+compTB)`**, with a single Compton cloud (tied coronal parameters) and no direct blackbody (`logA` = 8, frozen). In a similar fashion, the formula **`wabs*(nthcomp+nthcomp)`**, again with tied coronal parameters, was applied to successfully test different geometries for the two seed photon populations (the colder one being multicolour/disk-like).



The yellow dashes indicate observation of GCS (halo star population).
The two open circles indicate observation of 4U 1916-053.

The luminosity distribution

In the figure above the luminosity distribution of the whole set of analysed spectra is displayed.
The trend 1-P LHS -> 2-P LHS -> HSS with increasing luminosity (see also Table 1) is clear despite the obvious bias due to the distance, here assumed to be the same (8 kpc) for all the sources.
Of course there is a number of "odd balls", but generally the 1-P LHS clutser around a few 10^36 erg/s (<2% of the Eddington luminosity for a 1.4 M_sun NS), the typical 2-P luminosities are 10^37 erg/s (5% Eddington) and the HSS exceed 10% Eddington.
Concerning the LHS spectra, it's worth noting that, of the 3 faintest 2-P observations, one belongs to a GCS (M 15, halo population, located at 12 kpc) and the other two to 4U 1916-053, whose distance is estimated in the 8.5-10.5 kpc range (Smale et al., 1989).
On the other hand, these (and other) 2-P spectra with intensities lower or similar to that of 1-P's clearly indicate how 1-P spectra are intrinsically single-population, i.e. there is no (or negligible) counting statistics selection bias in the best fits.

Further remarks on the 1-P substate

UCXB connection

Most (8 out of 13) of the sources with 1-P spectra are firm ultra-compact binaries (UCXB) or UCXB candidates (see in't Zand et al., 2007). This is not surprising, as UCXB candidates are selected mainly because of their low persistent luminosity. Though the nature of UCX binaries is probably different from that of the brighter NS-LMXBs, their spectral characteristics look nevertheless related to the accretion rate: UCXB candidates are also detected in brighter, softer states (e.g. SLX 1735-269, 4U 1820-30, NGC 1851, 4U 1626-67, 4U 1543-624 in this *BeppoSAX* sample) or in a 2P sub-state (4U 0614+91, 4U 1916-053, Terzan 2, M 15 X-2).

Power-law hard states as 1-P states

The observed coronal temperatures, both in 1-P and 2-P sub-states, were never found to exceed 30 keV in the whole sample.

Even for the hardest BeppoSAX LHS spectra, where no cut-off can be firmly constrained (this is the case of the so-called *Power-Law* (PL) *hard states* observed in a number of *BeppoSAX* NS-LMXB transients), electron Compton temperatures kTe < 30 keV yield completely satisfactory fits. This suggests that the reported very high (> 30-50 keV) coronal temperatures of the PL hard NS sources are likely biased by the relatively poor counting statistics. And, actually, in this sample these objects are the faintest, and always associated to a 1-P LHS sub-state. In conclusion, there is no need to claim very high NS coronal temperatures, whenever the cut-off is unconstrained, if: *1)* a more typical < 30 keV corona fits the data and *2)* the spectrum displays a typical low-luminosity 1-P LHS sub-state, wholly similar to that of other non-PL sources.

NS vs BHC binaries

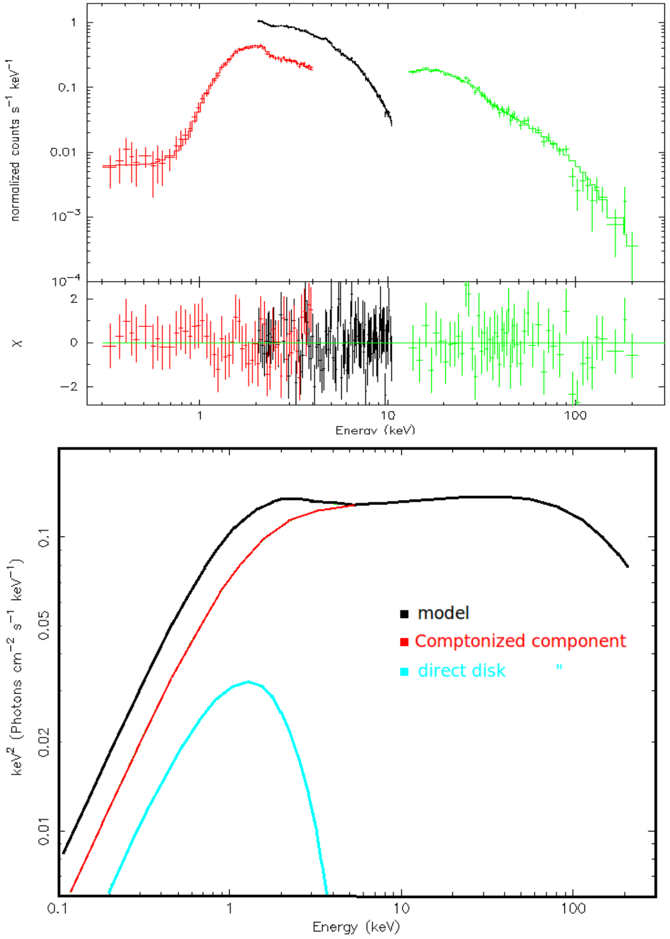
1-P LHS spectra are single photon population, as already observed in the case of the Black Hole Candidates (BHC) where the NS population is obviously missing.

Being 1-P LHS very faint (L < 10^37 erg/s) one can deduce that, whenever a single-population LHS spectrum is observed with luminosity in excess of (e.g.) 10^37 erg/s, the source is a likely BHC.

Moreover, as no coronal temperatures in excess of 30 keV were unambiguously observed in the whole *BeppoSAX* sample, one could deduce that very hot coronae (kTe > 30-40 keV) are peculiar of BHC objects only.

References

M. Cocchi, AIP, proc. AstroNS conf. Cesme 2010, in press (2011A)
M. Cocchi, R. Farinelli & A. Paizis, A&A, in press (2011B)
R. Farinelli et al., ApJ 680, 602 (2008)
M. Guainazzi et al., A&A 339, 802 (1998)
K. Mitsuda et al., PASJ 41, 97 (1989)
A. Smale, et al., MNRAS 232, 647 (1988)
L. Titarchuk, ApJ 434, 570 (1994)
N. White et al., ApJ 324, 363 (1988)
J. in 't Zand, P. Jonker & C. Markwardt, A&A 465, 953 (2007)
A. Zdziarski, W. Johnson & P. Magdziarz, MNRAS 283, 193 (1996)
P. Zycki, C. Done & D. Smith, MNRAS 309, 561 (1999)

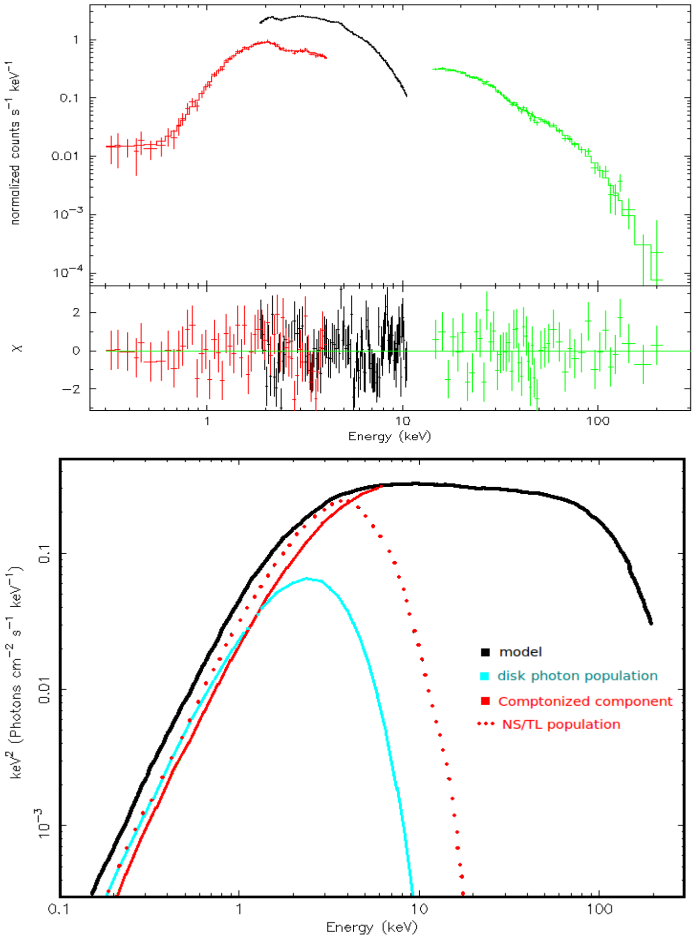


example of **1-P** spectrum: **4U 1812-12**

`wabs*(diskbb+nthcomp)`

wabs	nH	(1.58 +/- 0.05) x 10^22	cm^-2
diskbb	Tin	**0.71** +/- 0.03	keV
diskbb	R_in	**10.1** +/- 0.8	km (θ = 30°)
nthcomp	Gamma	**1.81** +/- 0.02	
nthComp	kT_e	[**25**]	keV
nthComp	kT_bb	= diskbb Tin	
nthComp	inp_type	[1]	

red. χ^2 = 0.96 (198 d.o.f.)

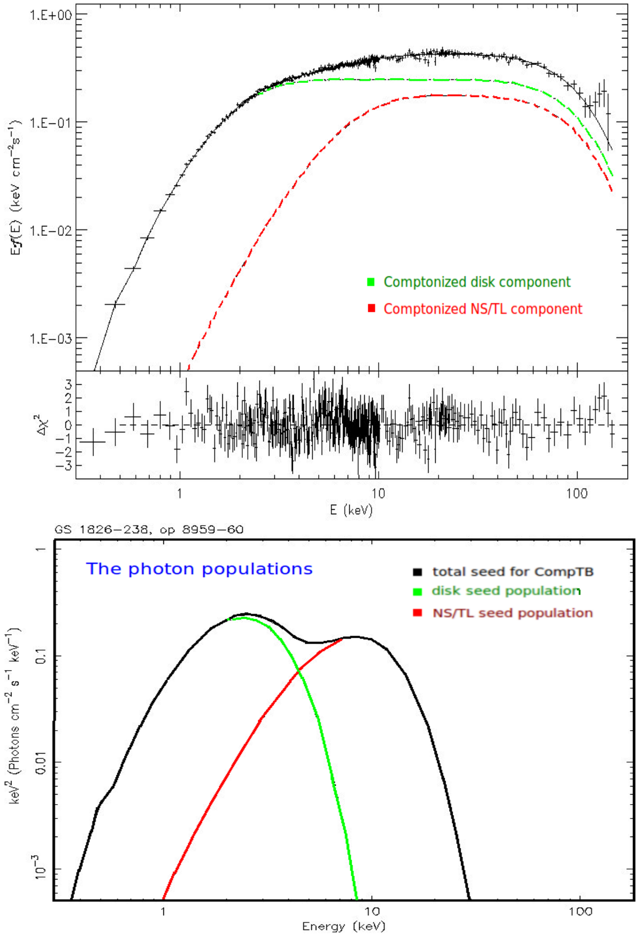


example of canonical **2-P** spectrum: **Terzan 2**

`wabs*(bbodyrad+compTB)`

wabs	nH	(0.79 +/- 0.03) x 10^22	cm^-2
bbodyrad	kT	**0.61** +/- 0.02	keV
bbodyrad	R	**9.7** +/- 0.5	km
compTB	kTs	**1.01** +/- 0.05	keV
compTB	alpha	**1.05** +/- 0.02	
compTB	kTe	**24.3** +/- 1.7	keV

red. χ^2 = 1.19 (200 d.o.f.)



example of fully Comptonised **2-P** spectrum: **GS 1826-238**

`wabs*(compTB+compTB)`

wabs	nH	(0.79 +/- 0.03) x 10^22	cm^-2
compTB1	kTs (DISK)	**0.48** +/- 0.01	keV
compTB2	kTs (NS-TL)	**1.68** +/- 0.09	keV
compTB	alpha	**0.98** +/- 0.02	
compTB	kTe	**19.2** +/- 0.8	keV

red. χ^2 = 1.10 (335 d.o.f.)