The soft X-ray spectrum of transient pulsars in the Small Magellanic Cloud

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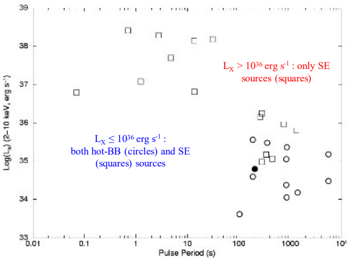
Spectral properties of High Mass X-Ray Binaries



X–ray spectrum between 0.1 and 10 keV:

- usually described by a rather flat power law (photon index $\Gamma \sim 1$) with an exponential cut-off
- often with Fe Kα emission lines

BUT

several XBPs have a marked data excess above the main power–law component (see *La Palombara & Mereghetti 2006*, for a review):

- Bright, transient sources ($L_X > 10^{36}$ erg s^{-1}): '*Soft*' Excess well described with a low temperature ($kT_{SE} < 0.5$ keV) and large emission area (R_{SE} > a few hundreds km) thermal emission model (either a blackbody, bremsstrahlung, or hot plasma emission)
- Low-luminosity, persistent sources ($L_X \le 10^{36}$ erg s^{-1}): instead of a SE, in some cases a '*hot BB*' excess of high temperature ($T_{BB} > 0.5$ keV) and small emission area ($R_{BB} < 2$ km) is observed.

Only in a few cases this low–energy component shows pulsations

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the debate about its origin remains open

Study of the soft part of the spectrum in Galactic sources affected by the interstellar absorption present in the Galactic plane

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only in few cases it is possible to detect and investigate the soft excess

Source[a]	Location	Distance (kpc)	Companion Star	P_{pulse} (s)	L_X^b (ergs s^{-1}, keV)	Flux (ergs cm^{-2} s^{-1})	N_H^c (10^{21} cm^{-2})	Lse/Lx	SE model[d]	kTnn (keV)	SE Pulses[e]
Her X–1[1]	Galaxy	~5	A7 V	1.24	1.0×10^{37} (0.3-10)	3.3×10^{-9}	0.05	0.04-0.10	BB, BB+LE	0.09-0.12	Yes
SMC X–1[2]	SMC	65	B0 Ib	0.7	2.4×10^{38} (0.7–10)	4.7×10^{-10}	2–5	0.036	BB, TB, SPL	0.15-0.18	Yes
LMC X–4[3]	LMC	50	O7 III–O IV	13.5	1.2×10^{38} (0.7–10)	4.0×10^{-10}	~0.5	0.064	BB, BB+TB, COM, SPL	0.15	Yes
XTE J0111.2–7317[4]	SMC	65	B1 IVe	30.95	1.8×10^{38} (0.7–10)	3.6×10^{-10}	1.8	~0.10	SPL	...	Yes
RX J0059.2–7138[5]	SMC	65	B1 IIIe	2.76	2.6×10^{36} (0.1–10)	5.1×10^{-10}	0.42-0.50	0.31	MEK, SPL	...	No
4U 1626-67[6]	Galaxy	?	Low-mass	7.7	$2.6\times10^{34}D^2_{kpc}$ (0.5-10)	2.2×10^{-10}	0.6	0.10	BB	0.34	No
Cen X–3[7]	Galaxy	~8	O6–O8 II	4.8	2.4×10^{38} (0.1–10)	3.2×10^{-8}	19.5	~0.7	BB	0.11	Yes
Vela X–1[8]	Galaxy	1.9	B0.5 Ib	283	2.2×10^{36} (2–10)	5.1×10^{-9}	4.2	~0.01	TB	...	No
X Per[9]	Galaxy	0.95	O9.5pe	837	1.8×10^{34} (0.3–10)	1.7×10^{-10}	1.5	0.24	BB	1.45	?
EXO 053109-6609.2[10]	LMC	50	B0.7 Ve	13.7	4.6×10^{37} (0.2–10)	1.5×10^{-10}	6.9	?	MEK+PL	...	Yes
A 0538–66[11]	LMC	50	B2 IIIe	0.069	4.0×10^{37} (0.1–2.4)	1.3×10^{-10}	0.8	?	BB, TB	~0.2	?
RX J0047.3-7312[12]	SMC	65	B2e	263	1.6, 2×10^{35} (0.7–10)	3.0, 4.0×10^{-12}	0.96,3.4	0.03-0.09,0.68	BB	0.6, 2.2	Yes
RX J0101.3-7211[13]	SMC	65	Be	452	1.0×10^{35} (0.3–10)	3.2×10^{-13}	0.6	?	MEK	...	?
RX J0103.6-7201[14]	SMC	65	O5 Ve	1323	$0.8-7.5\times10^{35}$ (0.2–10)	$1.6-14.8\times10^{-12}$	1.9	?	MEK	...	No
AX J0049.5-7323[15]	SMC	65	B2 Ve	751	$7-9\times10^{35}$ (0.2–10)	$1.4-1.8\times10^{-12}$	3.6	?	?	...	Yes
AX J0058-720[13]	SMC	65	Be	281	1.2×10^{35} (0.3–10)	2.4×10^{-13}	0.6	?	?	...	Yes
AX J0103-722[13]	SMC	65	B0 IV	342	1.8×10^{35} (0.3–10)	3.6×10^{-13}	0.6	?	MEK	...	?
3A 0535+262[16]	Galaxy	2.0	O9.7 IIIe	103.4	3.9×10^{33} (2–10)	8.2×10^{-12}	6.0	0.35	BB	1.33	?
RX J0146.9+6121	Galaxy	2.5	B0 IIIe	1395	1.5×10^{34} (0.3–10)	2.0×10^{-11}	5.1	0.25	BB	1.11	?

[a] References: (1) dal Fiume et al. (1998), Endo et al. (2000), Ramsay et al. (2002); (2) Woo et al. (1995), Paul et al. (2002); (3) Woo et al. (1996), La Barbera et al. (2001), Naik & Paul (2004); (4) Yokogawa et al. (2000b); (5) Kohno et al. (2000); (6) Schulz et al. (2001); (7) Burderi et al. (2000); (8) Haberl (1994), Orlandini et al. (1998), Kreykenbohm et al. (2002); (9) di Salvo et al. (1998), Coburn et al. (2001); (10) Haberl et al. (2003); (11) Mavromatakis & Haberl (1993); (12) The two set of values are base on Ueno et al. (2004) and Majid et al. (2004), respectively; (13) Sasaki et al. (2003); (14)Sasaki et al. (2003), Haberl & Pietsch (2005); (15) Yokogawa et al. (2000a), Haberl & Pietsch (2004); (16) Mukherjee & Paul (2005).
[b] For each source the reference energy range is also reported.
[c] The reported values refer only to the interstellar absorption, not to the source intrinsic absorption.
[d] Spectral models used for the soft excess are: BB = blackbody; TB = thermal bremsstrahlung; SPL = soft power–law or broken power–law; MEK = MEKAL thin thermal model; COM = Comptonization model; LE = broad low–energy line emission. Commas indicate separate fits, plus signs indicate fits with two components.
[e] Pulsation of the emission component that traces the soft excess.

Transient BeXRBs in the SMC

Ideal sources to investigate the *soft* spectral component in the HMXRBs:

- Several (> 100) sources
- $L_X \sim 10^{38}$ erg s^{-1} in outburst
- $N_H < 10^{21}$ cm^{-2}

} High count statistics at low energies

- Small uncertainties on the source distances ⇒ reliable estimate of L_X

Program of ToO observations with XMM started in 2011

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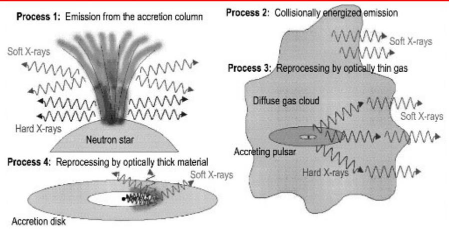
2 sources observed in *outburst*:

- RX J0059.2–7138 (March 2014)
- SMC X-2 (October 2015)

Hickox et al., 2004: the origin of the data excess depends on the luminosity of the source

$L_X \ge 10^{38}$ erg s^{-1}:	reprocessing of hard X-rays by the optically thick accretion material	SMC X-1, LMC X-4, Cen X-3, RX J0059.2-7138, XTE J0111.2-7317
$L_X \le 10^{36}$ erg s^{-1}:	emission by photoionized or collisionally heated gas or thermal emission from the neutron star surface	Vela X-1, AX J0103-722, RX J0101.3-7211 / 4U 1626-67, X Per
$L_X \sim 10^{37}$ erg s^{-1}:	either or both the above processes are possible	Her X-1, A0538-66, EXO 053109-6609.2



RX J0059.2-7138 (Sidoli et al. 2015, MNRAS 449)

1993:

- discovered with ROSAT (Hughes 1994)
- Pulse period of 2.76 s measured with ASCA (Kohno,Yokogawa & Koyama 2000)
- Observation of a spectral soft component (Kohno,Yokogawa & Koyama 2000)

December 2013: first observation of an *outburst* since 1993 (ATel 5756, Krimm et al. 2014), with $L_X \sim 7\times10^{37}$ erg s^{-1} (~ 3×10^{38} erg s^{-1} in 1993)

XMM-Newton observation:

- $P_{spin,2014}$ = 2.762383(5) s ⇒ spin-up compared to $P_{spin,1993}$ = 2.763221(4) s, with $\dot{P}_{spin}$ = -(1.27 ± 0.01)×10^{-12} s s^{-1}
- First detection of pulsed emission also at E < 0.5 keV
- Pulsed fraction ~ 10 % (~ 37 % in 1993)
- Significant SE which dominates the PL emission at E < 0.5 keV: $L_{SE} \sim 1.5\%\ L_{TOT}$ (~ 44 % in 1993)
- SE fit with either a BB (kT_{BB} = 93 eV, R_{BB} ~ 350 km) or a thermal plasma model (MEKAL, kT_{ME} = 210 eV, $R_{ME} > 6\times10^5$ km)
- first detection of spectral lines in HMXRBs in the MCs: several absorption and emission lines due to O, N, Ne and Fe
  - MEKAL not compatible with *soft* pulsations and various ionization states
  - $R_{repr} \sim 10^8$ km ~ R_m

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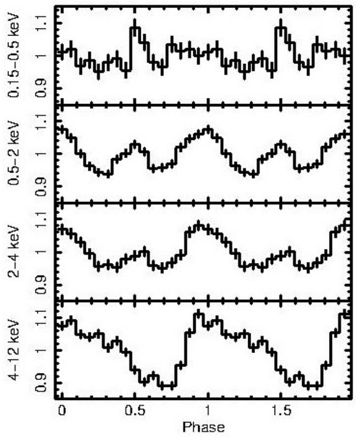
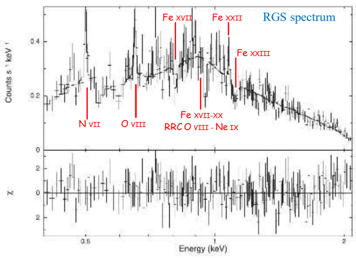
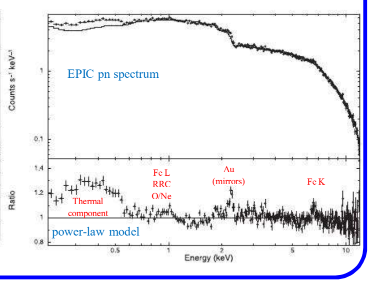
Reprocessing of the primary emission from the optically thick material in the inner region of the accretion disc







SMC X-2 (La Palombara et al. 2016, MNRASL 458)

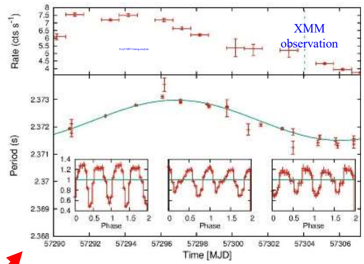
1977: discovered with SAS3 ($L_X = 8.4\times10^{37}$ erg s^{-1}; Li, Jernigan & Clark 1977; Clark et al. 1978); undetected one month later (Clark, Li & van Paradijs 1979)

2000: second *outburst* observed with RXTE ($L_X \sim 3\times10^{37}$ erg s^{-1}) ⇒ P_{spin} = 2.37 s (Corbet et al. 2001)

2011:

- OGLE: periodic variability of the optical counterpart (P = 18.62 ± 0.02 d, Schurch et al. 2011)
- RXTE: periodic modulation of the pulse period (P = 18.38 ± 0.02 d, Townsend et al. 2011)

September 2015: first observation of an outburst since 2000 (ATel 8088, Negoro et al. 2015; ATel 8091, Kennea et al. 2015), with $L_X \sim 10^{38}$ erg s^{-1} ~ $L_{X,1977}$

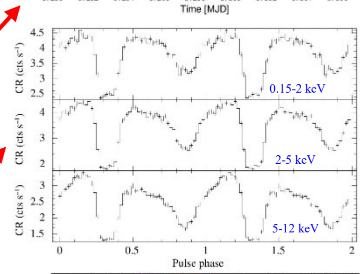


Swift/XRT timing analysis:

- 74 observations with *Swift*/XRT in *Windowed Timing* mode: P_{spin} = 2.37224(2) s, with modulations due to the orbital period P_{orb} = 18.38 ± 0.96 d

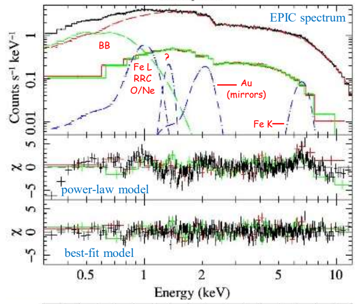
XMM-Newton timing analysis:

- $P_{spin,2015}$ = 2.372267(5) s ⇒ spin-down compared to $P_{spin,2000}$ = 2.37194(1) s, with $\dot{P}_{spin}$ = (6.6 ± 0.2)×10^{-13} s s^{-1}
- First detection of pulsed emission also at E < 0.5 keV
- Double-peaked pulse profile also at E < 0.5 keV, at odds with what observed with ASCA
- Pulsed fraction = 30-40 % (as in 2000)



EPIC spectrum:

- First observation of the SE (2-6 % of the total flux), which dominates at E < 0.5 keV
- SE fit with either a BB (kT_{BB} ~ 130 eV, R_{BB} ~ 320 km) or with emission from collisionally ionized gas (APEC, kT_{APEC} ~ 1.2 keV)
- First detection of Fe emission line



RGS spectrum:

- First detection of several emission lines due to O, N, Ne, Si e Fe
- APEC not compatible with *soft* pulsations and detected emission lines
- $R_{repr} \sim 10^8$ km ~ R_m

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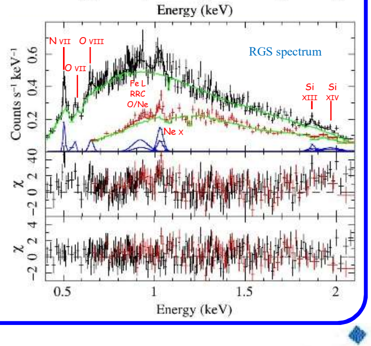
Reprocessing of the primary emission from optically thick material in the inner region of the accretion disc



Common properties of RX J0059.2-7138 and SMC X-2

- Characteristics SE: BB model, kT_{BB} ~ 0.1 keV, R_{BB} ~ 300 km, L_{BB}/L_{PL} = 2-3 %
- Emission lines due to O, N, Ne, Si e Fe
- $R_{repr} \sim 10^8$ cm
- $L_X \sim 10^{38}$ erg s^{-1} ⇒ pulsed fraction ~ 30-40 % (RX J0059 in 1993 and SMC X-2 in 2015)

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