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Authors	LA PALOMBARA, NICOLA, SIDOLI, Lara, Esposito, P., Pintore, Fabio, Tiengo, A., Mereghetti, S.
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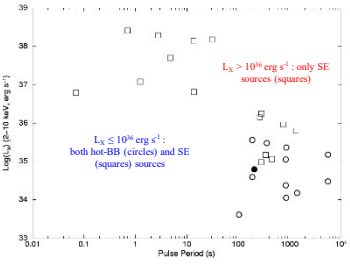
The soft X-ray spectrum of transient pulsars in the Small Magellanic Cloud

N. La Palombara[1], Lara Sidoli[1], Paolo Esposito[1], Fabio Pintore[1], Andrea Tiengo[2], Sandro Mereghetti[1]

(1 - INAF / IASF Milano, 2 - IUSS Pavia)

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 ($L_X \leq 10^{36}$ 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 (erg s^{-1}, keV)	Flux (erg cm^{-2} s^{-1})	N_H (10^{21} cm^{-2})	Lum/Lx	SE model[c]	kTsoft (keV)	SE Pulses[d]
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	0.69-0.12	Yes
SMC X-1[2]	SMC	65	Be fe	0.7	2.4×10^{38} (0.7-10)	4.7×10^{-10}	2-5	0.06	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^{36} (0.7–10)	5.6×10^{-11}	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^{-11}	0.42–0.50	0.31	MEK, SPL	---	No
4U 1626–67[6]	Galaxy	?	Low-mass	7.7	2.6×10^{34} D^2_{kpc} (0.5-10)	2.2×10^{-11}	0.6	0.10	BB	0.34	No
Cen X–3[7]	Galaxy	~8	O6–O8 II	4.8	2.4×10^{36} (0.1–10)	3.2×10^{-9}	10.5	~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^{-11}	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^{38} (0.1–24)	1.8×10^{-10}	0.8	?	BB, TB	~0.2	?
RX J0047.3–7312[12]	SMC	65	B2e	263	$1.5, 2 \times 10^{36}$ (0.7–10)	$3.0, 4.0 \times 10^{-12}$	0.96,3.4	0.05–0.09,0.68	BB	0.6, 2.2	Yes
RX J0101.3–7211[13]	SMC	65	Be	452	1.6×10^{35} (0.1–10)	2.2×10^{-13}	0.6	?	MEK	---	?
RX J0103.6–7201[14]	SMC	65	O5 Ve	1323	$0.8 - 7.5 \times 10^{36}$ (0.2–10)	$1.6 - 14.8 \times 10^{-12}$	3.9	?	MEK	---	No
AX J0043.5–7323[15]	SMC	65	B2 Ve	751	$? \quad 9 \times 10^{35}$ (0.2–10)	$1.4 \quad 1.8 \times 10^{-12}$	3.6	?	?	---	Yes
AX J0058–72[16]	SMC	65	Be	281	1.2×10^{35} (0.3–10)	2.4×10^{-13}	0.6	?	?	---	Yes
AX J0103–72[17]	SMC	65	B0 IV	342	1.8×10^{35} (0.1–10)	3.6×10^{-13}	0.6	?	MEK	---	?
3A 0535+262[18]	Galaxy	2.0	O9.7 IIe	103.4	3.9×10^{36} (2–10)	8.2×10^{-12}	6.0	0.35	BB	1.33	?
RX J0146.9+6121	Galaxy	2.5	B0 IIIe	1,395	1.5×10^{34} (0.1–10)	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. (2000), 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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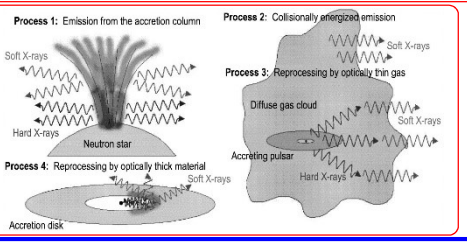
2 sources observed in *outburst*:
- RX J0059.2–7138 (March 2014)
- SMC X-2 (October 2015)

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

$L_X \geq 10^{38}$ 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
$L_X \leq 10^{36}$ 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

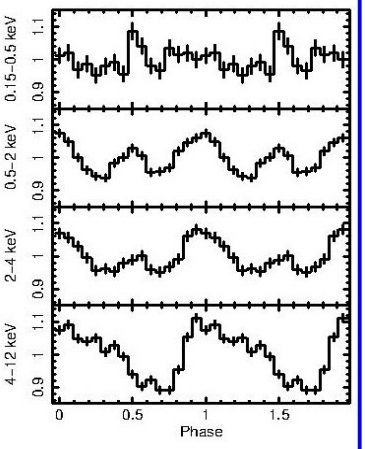


RX J0059.2-7138 (Sidoli et al. 2015, MNRAS 449)

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 $L_X \sim 7 \times 10^{37}$ 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 $\dot{P}_{spin} = -(1.27 \pm 0.01) \times 10^{-12}$ 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, $R_{BB} \sim 350$ km) or a thermal plasma model (MEKAL, $kT_{ME} = 210$ eV, $R_{ME} > 6 \times 10^5$ 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_{ns}

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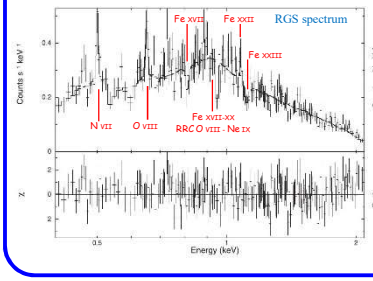
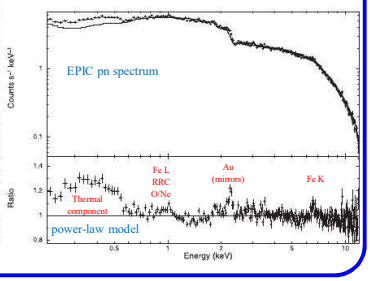
Reprocessing of the primary emission from the optically thick material in the inner region of the accretion disc





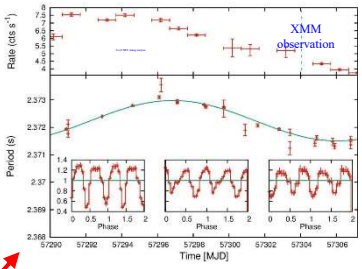
SMC X-2 (La Palombara et al. 2016, MNRASL 458)

1977: discovered with SAS3 ($L_X = 8.4 \times 10^{37}$ erg s^{-1}; Li, Jernigan & Clark 1977; Clark et al. 1978); undetected one month later (Clark, Li & van Paradijs 1979)

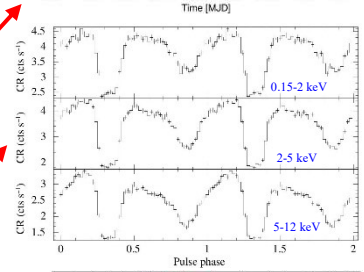
2000: second *outburst* observed with RXTE ($L_X \sim 3 \times 10^{37}$ erg s^{-1}) ⇒ $P_{spin} = 2.37$ s (Corbet et al. 2001)

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)

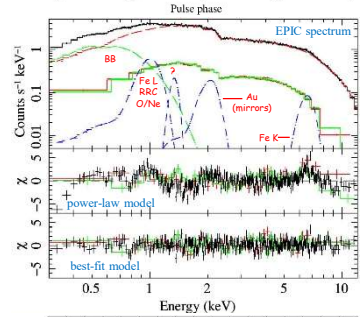
September 2015: first observation of an outburst since 2000 (ATel 8088, Negoro et al. 2015; ATel 8091, Kennea et al. 2015), with $L_X \sim 10^{38}$ erg s^{-1} ~ $L_{X,1977}$



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 $P_{orb} = 18.38 \pm 0.96$ d

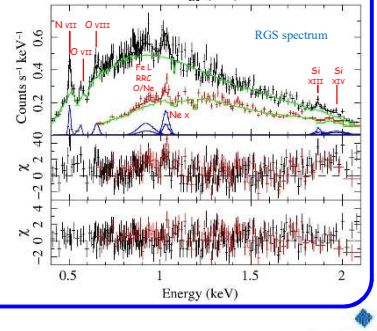


XMM-Newton timing analysis:
- $P_{spin,2015} = 2.372267(5)$ s ⇒ spin-down compared to $P_{spin,2000} = 2.37194(1)$ s, with $\dot{P}_{spin} = (6.6 \pm 0.2) \times 10^{-13}$ s s^{-1}
- First detection of pulsed emission also at E < 0.5 keV
- Double-peaked pulse profile also at E < 0.5 keV, at odds with 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 ($kT_{BB} \sim 130$ eV, $R_{BB} \sim 320$ km) or with emission from collisionally ionized gas (APEC, $kT_{APEC} \sim 1.2$ 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_{ns}

⇓

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, $kT_{BB} \sim 0.1$ keV, $R_{BB} \sim 300$ 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)