High mass X-ray binaries in a cosmological frame

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With recent observations from nearby and distant galaxies, the nature and the physical processes involved in the emission of high mass X-ray binaries (HMXBs) can be examinated in detail. In particular, the study of populations of HMXBs in cosmological simulations of galaxies can provide valuable hints on the nature of these sources.
In this work, we consider synthetic stellar population models that take into account the formation of HMXBs and incorporate them to galaxy catalogs from hydrodynamic cosmological simulations run with the code GADGET-3.
We study the number and X-ray luminosity (L_x) for nearby galaxies as well as their evolution with redshift comparing with recent observations. Our results suggests that the number of sources and likely also their X-ray luminosity depend on the metallicity of the stellar populations, which could explain the dispersion observed on L_x at low SFR. The evolution of the mean X-ray luminosity with redshift found in the observations is easily explained in our model by the dependence of L_x on the chemical composition of the parent stellar population.
This kind of models could be included in the future in simulations of galaxy formation to understand the possible role of black hole-HMXBs as stellar feedback and their relevance at early stages of the Universe.

High mass X-ray binaries (HMXBs) are systems composed of a compact object (neutron star NS or black hole BH) and a massive companion star. In these systems, matter is transferred from the companion star onto the compact object, via Roche lobe overflow or stellar wind capture. The accreted matter heats up and produces X-ray emission.

Cosmological simulation

* We use galaxy catalogs from hydrodynamical cosmological simulations performed with a version of GADGET-3.

*This version includes:
 * Multiphase model for the interstellar medium and SN feedback scheme (Scannapieco et al. 2005,2006).
 * Star formation, metal-dependent cooling, chemical enrichment.
 * 230^3 particles of dark matter and 230^3 of gas particles with masses of 5.93 $10^6 M_{sun}\ h^{-1}$ and 9.1 $10^5 M_{sun}\ h^{-1}$, respectively.
 * Type II and Type Ia SNe feedback for chemical and energy production (0.7×10^{51} erg per event).

*Cosmological parameters: $\Omega_\Lambda=0.7$, $\Omega_m=0.3$, $\Omega_b=0.004$, $\sigma_8=0.9$, $H_0=100h$km/s, $h=0.7$

*Periodic co-moving volume of 10 Mpc/h side.
*Virialized structures are selected from the general mass distribution by using a FoF technique, and SUBFIND algorithm was applied for identify substructures.

*This simulation was applied in the study of stellar and barionic Tully-Fisher relation, finding good agreement with observational results (De Rossi et al. 2010).

*For each snapshot, we generate a galaxy catalog with those structures above 3000 particles, which is equivalent to have stellar masses higher than $10^8 M_{sun}\ h^{-1}$.

*Galaxies in our simulation have lower mean metallicity than observed (Tremonti et al. 2004). We renormalize the simulated abundances to make them consistent with observations (Maiolino et al. 2008).

Population Synthesis

* Only young stellar populations with ages τ_{cut}=100Myr produce HMXBs.
* We compute the number of NS and BH produced by each young stellar population according to the model of Georgy et al. (2009).
* For a stellar population *p* formed at redshift *zp*, with a mass $m_{*,p}$ and metallicity Z_p:

$$N_{\rm p}^{\rm BH,NS} = m_{*,\rm p}\frac{\int_{R^{\rm BH,NS}(Z_{\rm p})}\xi(m)dm}{\int_{0.1\,M_\odot}^{100\,M_\odot}m\xi(m)dm},$$

*$R_{BH,NS}(Zp)$:mass range over which each type of compact remnant is produced at metallicity Z_p, and $\xi(m)$ is the IMF (Salpeter) with 0.1M_{sun} and 100M_{sun} lower and upper cut-offs, respectively.

* We include a chemical dependent model from Belczynski et al. (2004) to estimate the rate of BH and NS in binary systems ($f_{b,BH}(Zp)$, $f_{b,NS}(Zp)$).

*The intrisic number of HMXB systems produced in each stellar population in our galaxy catalogs is:
$N_{HMXB}(Zp)=f_{b,BH}(Zp)\,N_{BH}(Zp) + f_{b,NS}(Zp)\,N_{NS}(Zp)$

* To account for effects that we can not model (transient sources, duty cicle and exact lifetime of HMXBs) we consider a normalization factor η.
And we available observations for nearby galaxies (Mineo et al. 2012) to constrain this value.

* We assume an X-ray luminosity function (XLF) derived form observation of HMXBs in the local Universe $\log\Psi(L_x)\sim\alpha\log L_x$ α=-1.6 in $\log L_x$ Є [36,40]erg/s (Mineo et al. 2012).

* We also explore models in which XLF varies with metallicity of the parent stellar population (Dray et al. 2006).

* We take into account the detectability of X-ray emission for each galaxy:
 * In nearby galaxies satellites detect HMXBs as point sources. Only sources with $L_x>L_{x,lim}=4\pi R^2F_x$ ($L_{x,lim}$ correlated with SFR, Mineo et al. 2012) are observable.
 * For distant galaxies: only the cumulative X-ray luminosity is detected. We discard galaxies with $L_{x,g}<L_{x,lim}=4\pi R(z)^2F_x$.

Model	$\log\langle L_X(Z_1)\rangle$	$\log\langle L_X(Z_2)\rangle$	$\log\langle L_X(Z_3)\rangle$
0	38.1	38.1	38.1
1	39.3	38.9	38.1
2	39.7	38.1	38.1
3	39.7	38.5	38.1
4	39.7	38.9	38.1
5	38.9	38.5	38.1

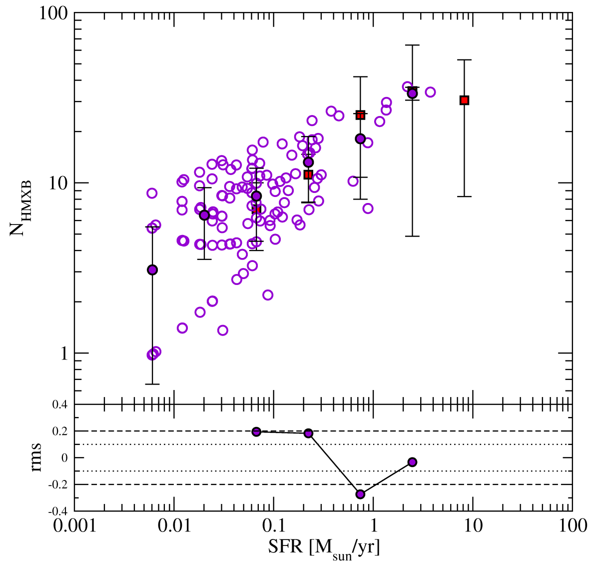


Fig 1: Number of HMXBs as a function of SFR for nearby galaxies

*We use the number of HMXBs in nearby galaxies to determine the normalization factor η.
*A best fit value η = 0.0025 describes well the mean number of HMXBs in the sample of Mineo et al. (2012).

*Empty and filled violet circles: represent N_{HMXB} for our galaxy catalog and their means at fixed SFR bins, respectively.
*Filled red squares: represent the mean number of HMXBs from the primary sample of Mineo et al. (2012) binned in the same way (galaxies resolved by Chandra).

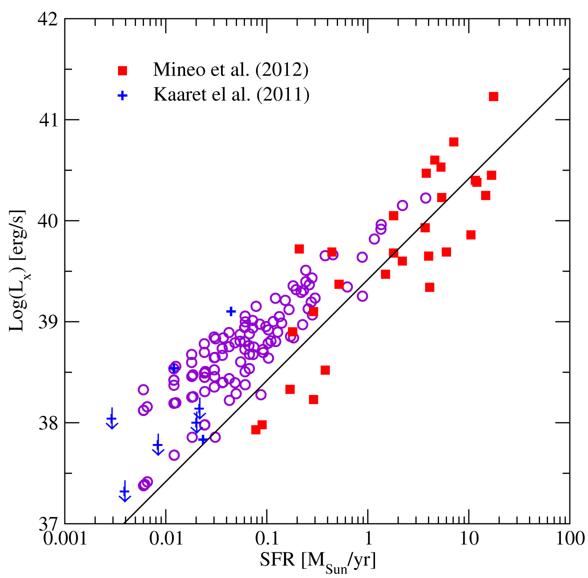


Fig 2: Cumulative X-ray luminosity as a function of SFR for nearby galaxies

* We obtain the same trend than observations for nearby galaxies, but we overestimate the cumulative X-ray luminosity at low rates of SFR.

* This fact makes chemistry-dependent models to describe dwarf galaxy data better (Kaaret et al. 2011).

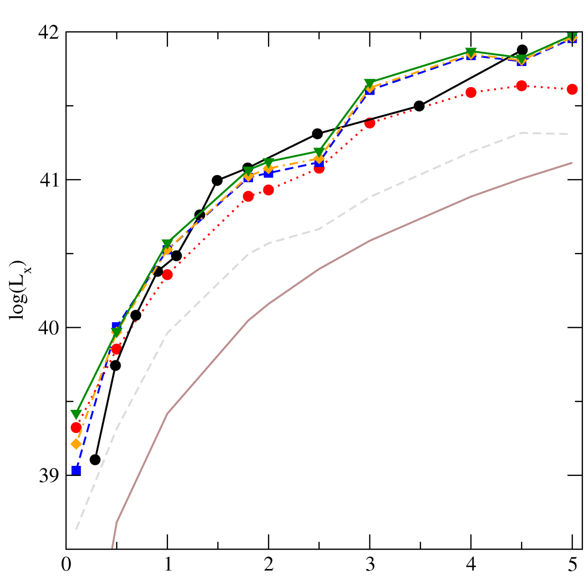
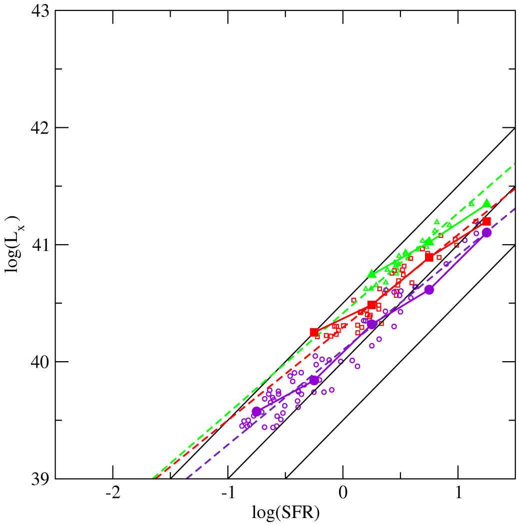


Fig 3: Mean X-ray luminosity of galaxies as a function of redshift

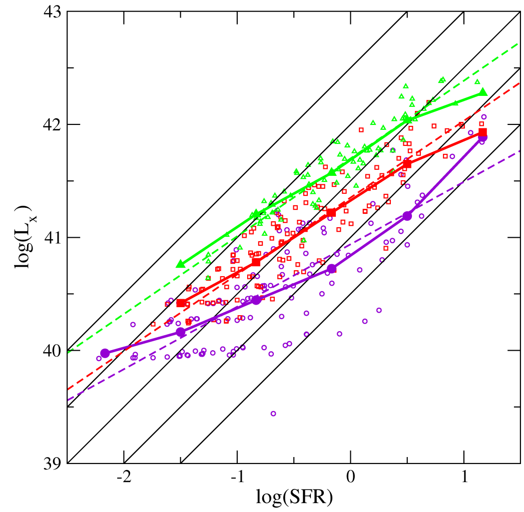
*Black filled circles represent observations from Cowie et al. (2012), grey dashed line represent model 0, while brown solid line represent the luminosity threshold.
*Four different models with chemistry-dependent mean luminosities are plotted: model 1 (red circles), model 2 (best fit, blue squares), model 3 (yellow diamonds) and model 4 (green triangles).

* The increase of the mean Lx of galaxies with redshift displayed by the high-redshift sample, can be described only by models in which the luminosity of HMXBs is metallicity dependent.

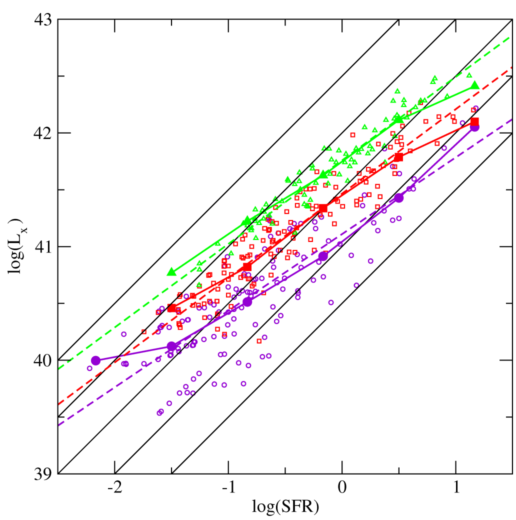
*Mean X-ray luminosity is higher for high redshifts as a consequence of chemical evolution of the Universe.



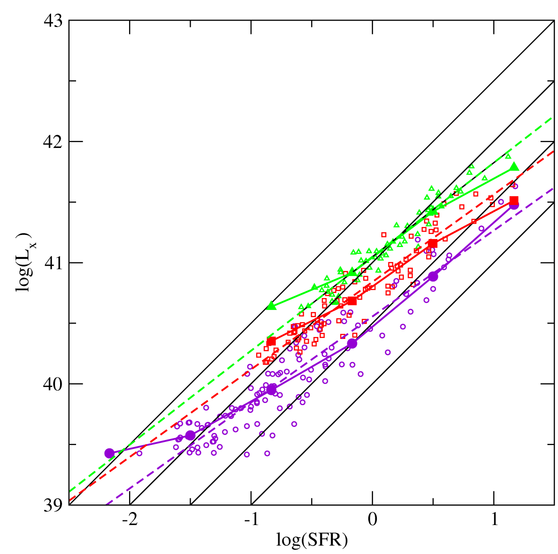
Model 0



Model 2



Model 4



Model 5

Fig 4: Log Lx – log SFR relation

* We studied the relation for redshift 1 (violet circles), 2 (red squares) and 3 (green triangles) in four of our models (model 0 non XLF chemical dependent, and three with XLF chemical dependent).
* log Lx - log SFR relation remains roughly linear at different redshift, but its zero point increases with redshift in metallicity dependent models.
* This increase can be explained as due to the chemical evolution of the Universe.
* At higher redshift the metallicity decreases and HMXBs become brighter and more numerous.

Conclusions

*We developed a model for the X-ray emission of HMXBs populations in galaxies, taking onto account the possible metallicity dependence of the HMXBs formation rate and HMXBs luminosities.
*We constrain the free parameters of our models fitting the observed number of HMXBs in nearby galaxies as a function of their SFR.
*With this constraints and taking into account detectability issues and selection effects, our model reproduces fairly well the observed X-ray luminosities of star-forming nearby galaxies.
*However, to reproduce the observed X-ray luminosities of high-redshift galaxies, a strong dependence of the HMXB luminosities on metallicity must be assumed.
*This is in line with recent observations and theoretical models that suggest that the masses of the most massive black holes increase at decreasing metallicities (Linden et al. 2010).

Currently and in the future...

X-ray binaries potential sources of stellar feedback?

* By using ionization nebulae around ULXs as calorimeters, Pakull & Mirioni 2003 found that energy deposited in the nebulae was comparable to the observed X-ray luminosity. Similar results assuming isotropic X-ray emission are presented in Roberts et al. 2003.
(Pakull & Mirioni 2003: We derive that a kinetic energy for a typical supernova, and has led to the suggestion that the bubble was powered by a “hypernova“ during which the black hole in the ULX was formed).

*Cantalupo et al. 2010 and Sawala et al. 2011: The effect of photo-ionization by local sources on the gas cooling for low and intermediate mass galaxies might be a physical mechanism to regulate star formation.
(Photoionization by local sources would be able to regulate gas accretion and SF, without the need for additional strong feedback processes).

*Justam & Schawinski 2012: suggest that large stochastic variation in the magnitude of X-ray binaries feedback at low SFR provides a natural explanation for the diversity in the evolution of dwarf galaxies.

*Considering that HMXB can reach luminosities in the order of ~10^{39}erg/s and might emit X-rays for ~20Myr, these sources could introduce ~10^{53}erg into the surrounding gas.