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Hard X-rays emitted by starbursts as predicted by population synthesis models including a realistic fraction of interacting binaries

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Abstract. We combine our close binary population number synthesis code with the formation mechanism of X-radiation in young supernova remnants and in high mass X-ray binaries, to predict the hard X-ray luminosity emitted by starbursts. We demonstrate that the impact of interacting binaries is substantial. Therefore, observations of hard X-rays with energies larger than 2 keV of starburst regions may highlight the importance of close binary evolution in understanding properties of active starformation regions.

Key words: stars: binaries: close – ISM: supernova remnants – galaxies: starburst – galaxies: stellar content – X-rays: stars

1. Introduction

The discovery of emission line galaxies in the early seventies (Sargent & Searle 1970; Searle et al. 1973) started a new era in population synthesis studies: the evolution of young and massive starbursts. In a few million years, massive stars evolve into WR stars, i.e. after a few million years massive starbursts start showing WR features. Conti (1991) was the first to introduce the *WR galaxy* nomenclature and listed 37 candidates. This number has increased up to about 130 (Schaerer et al. 1999). Theoretical population synthesis models of starbursts have been calculated by Mass-Hesse & Kunth (1991), Leitherer & Heckman (1995), Leitherer et al. (1995), Meynet (1995), considering single stars only. Binaries were included by Vanbeveren et al. (1997), Schaerer & Vacca (1998), Vanbeveren et al.(1998a), Van Bever & Vanbeveren (1998), Van Bever et al. (1999), Mas-Hesse & Cervino (1999). Obviously, their influence depends on the adopted binary frequency in starbursts and this is still a matter of debate. A way out may be to observe features which are due to binaries only. A population of massive binaries evolves into a population of high mass X-ray binaries. Since high mass X-ray binaries emit hard X-rays (≥ 2 keV), it may prove useful to observe the hard X-ray spectrum of starbursts and to compare with theoretical prediction. Many emission line galaxies were detected as [2-10] keV X-ray emitters by the Advanced Satellite for Cosmology and Astrophysiscs (ASCA; Tanaka et al. 1994). A number of them can be found in the minisurvey of Dahlem et al. (1998). Typical X-ray luminosities range between 10^{39} and 10^{41} erg/s (see also Della Ceca et al. 1997,1999). The X-ray spectrum in most of them may reflect the presence of high mass X-ray binaries (HMXB) and/or energetic isolated young pulsars (young supernova remnants = YSNR), although the contribution of low luminosity AGN may be very significant as well (Ptak et al. 1997,1999).

The prototype WR galaxy Henize 2-10 has been detected by ASCA in the [2-10] keV band (Ohyama & Taniguchi 1999). The absorption corrected X-ray luminosity in this passband is about 10^{39} erg/s and the spectrum is relatively hard (kT ≈ 3.9 keV). It is concluded that HMXBs and YSNRs have to be present in the starburst. The WR galaxy I Zw 18 is, similarly as Henize 2-10, a blue compact dwarf galaxy but with a very low metallicity (Z = 0.0005). It has not been observed by ASCA but it was detected by ROSAT (Stevens & Strickland 1998a,1998b). Most of the WR galaxies detected by ROSAT have a soft thermal X-ray spectrum with kT ≈ 0.4 - 1 keV, which is consistent with a young starburst model whose X-ray emission comes from superbubbles. However, the spectrum of I Zw 18 is significantly harder (≥ 2 keV) and this may indicate an origin other than superbubbles. The 30 Doradus complex in the LMC contains the luminous star cluster R 136. Within the cluster, there are 39 O3 type stars (Massey & Hunter 1998). The latter authors concluded from this that the cluster is very young (1-2 million years). In the field of R 136, 2 (hard) X-ray sources were detected by Wang (1995) and the author proposes a binary nature for the X-radiation. If these sources belong to the cluster, we will demonstrate that this may further constrain the cluster's age and the importance of binaries in starbursts. Using a population synthesis code with a realistic fraction of binaries, it is the scope of the present paper to study the predicted hard X-rays emitted by YSNRs and HMXBs in a starburst.

2. The population synthesis model

Population number synthesis (PNS) models for massive stars with a realistic frequency of massive close binaries have been constructed by different groups (Dewey & Cordes 1987; Meurs & Van den Heuvel 1989; Pols et al. 1991; Pols & Marinus 1994; Tutukov et al. 1992; Iben et al. 1995a,1995b; Lipunov et al.

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1996; Jorgensen et al. 1997; Dalton & Sarazin 1995a,1995b; Portegies Zwart & Verbunt 1996). The overall physics of the binary evolutionary scenario is similar in all models. The main difference between our code and others concerns the treatment of the effect of the supernova explosion of one of the components of a massive binary on the orbital parameters of the latter and the stellar evolutionary results that are used. To follow the evolution of young starbursts and to estimate the X-radiation from YSNRs and HMXBs, it is essential that the most recent computations are implemented whereas the evolution of mass gainers must be followed in detail. Our PNS model uses an extended library of stellar evolutionary calculations (Vanbeveren et al. 1998a,1998b,1998c) in which we adopt the most recent stellar wind mass loss rate formalisms. Especially the rates during the luminous blue variable (LBV) phase, during the red supergiant (RSG) phase and during the WR phase affect in a critical way the results of population synthesis. To illustrate: when a massive star has lost most of its hydrogen rich layers (either due to LBV stellar wind, due to RSG stellar wind, or due to mass loss phases which are typical for binaries, e.g. Roche lobe overflow = RLOF, the common envelope process and/or the spiral-in process), and becomes a blue hydrogen poor core helium burning (CHeB) star, it can be classified as a WR star and thus, to calculate its evolution, WR-like mass loss rates must be used.

Woosley et al. (1993) followed the evolution up to Fe-core collapse of massive stars who have lost all their hydrogen during hydrogen shell burning and became hydrogen poor at the beginning of CHeB (a situation typical for primaries in close binaries that lose their mass by RLOF). During CHeB the stellar wind mass loss rate formalism of Langer (1989) was used for WR stars. These evolutionary computations predict that all massive primaries end their life with a mass between 2.5 $M_{\odot}$ and 5 $M_{\odot}$. However, some X-ray binaries have a very massive black hole component, e.g. Cyg X-1 has a black hole component with a mass $> 10\ M_{\odot}$ (Gies & Bolton 1986). If the mass is confirmed, it is incompatible with the previous WR mass loss formalism. New hydrodynamical analysis of WR atmospheres point towards much lower stellar wind mass loss rates. The WR mass loss rates listed by Hamann & Koesterke (1998) are a factor of 4 smaller than those predicted by the formalism of Langer (1989). Including line-blanketing and clumping, Hillier & Miller (1999) analyzed the WC5 star HD 165763 and derive $Log(L/L_{\odot}) = 5.3$ and $Log\ \dot{M} = -4.8$ ($\dot{M}$ in $M_{\odot}/yr$). Schmutz (1997) obtained $log\ L = 5.7$ and $log\ \dot{M} = -4.5$ for the hydrogenless WN5 star HD 50896. The mass loss rate derived for the binary V444 Cyg from the orbital period increase yields a value $log\ \dot{M} \approx -5$ (Underhill et al. 1990). The luminosity of the WR component is $Log(L/L_{\odot}) = 5$.

Vanbeveren et al. (1998a,1998b) investigated the consequences of a WR mass loss formalism that fits the three observations listed above ($Log\ \dot{M} = Log(L/L_{\odot}) - 10$). Compared to the results of Woosley et al. (1993), the pre-Fe-core collapse masses are significantly larger and the existence of HMXBs like Cyg X-1 can be explained in a straightforward way. Although it is clear that much more observations are needed to confirm these smaller mass loss rates, the evolutionary calculations that are used in our PNS code rely on them. We like to repeat here two PNS ingredients that are of particular importance for the results of the present paper:

• As a consequence of an asymmetrical SN explosion, a neutron star remnant receives a kick velocity v_{kick}. When a SN explosion occurs in a binary, the direction and magnitude of the kick obviously affect the binary parameters. Our PNS code includes a detailed binary SN model and we use a v_{kick} distribution which relies on the study of Lorimer et al. (1997).

• When the final CO-core masses at the end of CHeB are linked to the post-CHeB evolutionary calculations of Timmes et al. (1996) (see also Fryer 1999), it follows that

All single stars (resp. primaries of interacting close binaries) with initial mass $\geq 25\ M_{\odot}$ (resp. 40 $M_{\odot}$) finally collapse to form a black hole.

These mass limits are used in our PNS calculations. Note however, that if stellar wind mass loss rates depend on the metallicity as predicted by the radiatively driven wind theory (Kudritzki et al. 1987), the mass limits may be smaller in low metallicity environments.

In our PNS computations, we do not account for the effects on binary parameters of a possible supernova explosion prior to the black hole formation. This may not be correct. The low mass X-ray binary GRO J1655-40 (Nova Scorpii 1994) consists of a black hole candidate with a mass $\approx 6 \pm 2\ M_{\odot}$ whereas the optical component is an F3-F8 IV/III star with mass $\approx 2.35 \pm 0.75\ M_{\odot}$ (Shahbaz et al. 1999). It was shown by Israelian et al. (1999) that O, Mg, Si and S are significantly overabundant in the atmosphere of the optical component. This is considered as evidence that a supernova explosion occurred prior to BH formation and that supernova ejecta were captured by the F star.

To simulate the evolution of a starburst, we proceed as follows. Given a large number of stars (we have chosen $3 \cdot 10^5$ massive objects, an object being either a single star with initial mass between 10 $M_{\odot}$ and 100 $M_{\odot}$, or a binary with primary mass between 10 $M_{\odot}$ and 100 $M_{\odot}$), we use a Monte-Carlo method to simulate the population, given a binary frequency at birth, an initial mass function which is assumed to be similar for single stars and for primaries of binaries, a mass ratio and period distribution of binaries. When a binary component or single star ends its life as a neutron star and thus a supernova explosion occurs, again using a Monte-Carlo method, our PNS code also decides upon the v_{kick} (magnitude and direction) and the magnetic field B according to their respective distributions. The distribution of the direction of the kick is assumed to be isotropic. Details of the PNS model and the adopted distribution functions have been discussed by Vanbeveren et al. (1998a) and by Van Bever & Vanbeveren (1998).

3. The population of hard X-ray emitters

In young starbursts, hard X-radiation with energies larger than 2 keV are produced mainly by YSNRs and HMXBs.

3.1. YSNRs

YSNRs radiate a synchrotron X-ray spectrum that can be modeled by a Raymond-Smith model with a temperature kT ≈ 2 keV (Della Ceca et al. 1999; Ohyama & Taniguchi 1999). The formation of X-rays from young single pulsars has been outlined in classical papers like Goldreich & Julian (1969), Goldreich et al. (1971), Rees & Gunn (1974). The pulsar loses rotational energy at a rate

$$\dot{E} = I\Omega\dot{\Omega}\,, \tag{1}$$

(I = the moment of inertia of the neutron star, Ω the angular velocity) in the form of electromagnetic waves and in the form of a relativistic wind containing a toroidal magnetic field. Part of this energy is radiated as X-rays, i.e.:

$$L_x = \eta\dot{E} \qquad 0 < \eta < 1\,, \tag{2}$$

Seward & Wang (1988) used *Einstein* observations to measure the X-ray luminosity L_x in the band 0.2 - 4 keV of pulsars and their associated nebulae. They considered pulsars whose rotational period P and its derivative are known and concluded that $\eta \approx$ 0.01 - 0.03. We will use 0.03 but it must be realized that the X-ray luminosity of SNRs predicted by population number synthesis scales linearly with η. The energy rate as a function of time is calculated using the following relation between the magnetic field B of the neutron star, its period and period derivative:

$$B = 3.2 \cdot 10^{19}\sqrt{P\dot{P}} \quad (Gauss)\,, \tag{3}$$

(with P in s and $\dot{P}$ dimensionless). The relation holds for a standard neutron star if the torque that causes the spin down is due to dipole radiation only (pulsar breaking index n = 3). Although observations of the Crab pulsar and PSR 1509-58 seem to indicate slightly smaller values (Manchester et al. 1985), the foregoing relation is more than sufficient for PNS calculations.

To estimate the X-radiation produced by SNRs by means of a PNS code we thus need to know the distribution of B and the distribution of initial spin period of neutron stars. The distribution of B appears to be Gaussian in log B, with average ≈ 12.5 (B in Gauss) and standard deviation ≈ 0.3 (Bhattacharya et al. 1992). However, nothing much can be said about the initial spin period of neutron stars. The present day spin period distribution and the B distribution are consistent with the conclusion that most of the neutron stars are born with a period $<$ 0.1 s. All pulsars that are still embedded in the SN nebula (and which are thus very young) have a pulse period larger than 0.01 s. We will calculate our PNS model assuming that all pulsars are born with the same spin period P_0 ranging from 0.001 - 0.1 s. Since the total rotational energy of a pulsar is proportional to P^{-2}, it can be suspected that the result may depend on P_0. In our PNS code, we apply the foregoing formalism to all single and binary pulsars, also to those who became single after disruption of the progenitor binary due to the supernova explosion. When, after the supernova explosion, the pulsar remains attached to the OB component, X-rays are produced by the process described in the next subsection.

3.2. HMXBs

Using a Monte-Carlo simulation, our PNS model predicts the population of OB type stars with a compact companion (cc) resulting from a population of massive stars with a realistic fraction of close binaries. For each OB+cc system that is formed, we know its period, the mass and spectral type of the OB components, whether the cc is a neutron star or a black hole. The subsequent evolution of the OB-type star is followed in detail. When an OB+cc binary survives the spiral-in process and a WR+cc is formed, the evolution of the WR star is followed till the end of CHeB using the appropriate stellar wind mass loss rate formalism. An OB/WR + cc binary becomes a HMXB when part of the matter lost by the optical component is trapped gravitationally by the cc. The X-ray energy is essentially the loss of gravitational energy of this matter. However, to obtain X-rays, it is essential that an accretion disc is formed (Shapiro & Lightman 1976) and/or a very strong magnetic field is present (Langer & Rappaport 1982). The former condition is particularly important when the cc is a black hole which cannot support a magnetic field. In this case, a Keplerian disc is formed when the specific angular momentum of the accreted matter exceeds the specific angular momentum of the matter in the last stable orbit in the disk ($R_K \approx 3$ times the Schwarzschild radius). The latter condition is fulfilled when (e.g. Iben et al. 1995a)

$$\frac{R}{A} \geq \left(1 - \frac{R}{A}\right)^{\frac{8}{7}} \left(\frac{R_K}{R}\right)^{\frac{1}{7}} \left(\frac{M}{M_{cc}}\right)^{\frac{3}{7}}\,, \tag{4}$$

(R and M are resp. the radius and mass of the optical component, A is the semi major axis, M_{cc} is the mass of the compact star).

To calculate the X-radiation of an OB/WR+cc, we first check condition (4) and we distinguish the following subclasses.

• *HMXB*$_1$: the OB type star is a core hydrogen burning (CHB) star with mass larger than about 20 $M_\odot$, losing mass by stellar wind at moderate rates. The X-rays are due to the accretion of mass of the stellar wind by the compact star. We use the description of Davidson & Ostriker (1973) combined with a typical radiatively driven stellar wind model of the OB star (Kudritzki 1987). We will illustrate in Sect. 4 that the contribution of this class of HMXBs to the total predicted X-radiation of a starburst is small due to the fact that in most cases the mass accretion rate onto the compact object is small.

• *HMXB*$_2$: the OB type star fills its critical Roche lobe while it is a CHB star. The subsequent evolution is governed by the spiral-in process. Due to the fact that the OB star evolves on the nuclear timescale, the system may be visible as a bright X-ray source in a phase of beginning spiral-in (Savonije 1979,1983). We adopt as a (simple) model that all the systems in our simulation that enter such a phase radiate at the critical Eddington luminosity and the timescale of this phase (as function of system period and mass of the optical star) is estimated from the two papers of Savonije.

• *HMXB*$_3$: the OB type star is a hydrogen shell burning supergiant with a strong stellar wind. In this case, the X-ray luminosity is close to the critical Eddington value. For simplicity, we use the latter value. The time scale of this X-ray phase depends on:

1. the period of the HMXB which fixes the onset of the spiral-in phase and
2. the details of the spiral-in process itself,

but obviously, it must be of the order of the thermal timescale τ_{KH}.

• *HMXB*$_4$: B emission line X-ray binaries. The optical star is unevolved with spectral type between O9Ve and B2Ve, in some cases subgiants, and their mass range between 8 $M_\odot$ and $\approx$ 20 $M_\odot$. Be stars show two mass loss modes: a weak persistent stellar wind which is responsible for a weak (persistent) X-ray emission with luminosities of about 10^{32}-10^{34} erg/s, and equatorial mass ejection which occur at completely erratic intervals (presumably due to some combination of rotation and non-radial oscillations). During such outbursts, the X-ray luminosity may increase up to 10^{37}-10^{38} erg/s. Since the physics of the outbursts is still poorly understood, it is difficult to make any estimate of the X-radiation of a starburst once the HMXBs are dominated by OB + cc binaries for which the OB star mass is smaller than about 20 $M_\odot$.

• *HMXB*$_5$: the optical component is a WR star. We use a similar formalism as for $HMXB_1$'s but with a typical WR stellar wind. WR wind rates are significantly larger than OB rates. To estimate the X-radiation produced by WR+cc binaries, it is therefore very important to account for the absorption of X-rays by the stellar wind of the WR star itself. The latter depends on the orbital phase of a WR+cc binary and on the details of the WR atmosphere. We use the procedure outlined by Vanbeveren et al. (1998b) and, to obtain an average value, for all WR+cc binaries predicted by our PNS model we calculate the effect of the absorption of X-rays at orbital phase $\pi/2$.

The observed X-ray spectrum of most of the HMXBs with a neutron star companion can be compared with the radiation of a thermal plasma with kT $\geq$ 15 keV (Nagase 1989). Compared to HMXBs with a neutron star, the X-ray spectrum of black hole candidates may be significantly softer or may contain a soft component (Tanaka & Lewin 1994). The cc in Cyg X-3 is probably a black hole (Schmutz et al. 1996) whereas during the high state of the X-ray emission, its X-ray spectrum can be described by a bremsstrahlungspectrum with kT $\approx$ 4 keV (Vanbeveren et al. 1998b). As a consequence, we can expect that

when the HMXB population in a starburst is dominated by black hole candidates, the emitted X-ray spectrum may be significantly softer than when it is dominated by neutron star candidates.

Interestingly, the X-ray spectrum of the emission line galaxies and of the WR galaxy Henize 2-10 discussed in the introduction seem to be harder than predicted by YSNRs but softer than spectra of HMXBs with a neutron star component. This may indicate that, if HMXBs are responsible for at least part of the X-radiation in these starburst regions, black hole HMXBs are the most likely candidates. Due to the limited signal-to-noise spectra obtained by ROSAT and ASCA, the latter suggestion is still very uncertain. New observations with CHANDRA and XMM will provide more accurate measurements of the hard component in these galaxies, which should allow us to discriminate on the relative number of HMXBs with BH-candidates and HMXBs with neutron stars.

4. Results and discussion

We define a *standard starburst* as an instantaneous burst of $3 \cdot 10^5$ massive objects, the IMF of single stars and of primaries of binaries follows a Salpeter slope, a flat binary mass ratio distribution, a binary period distribution that is flat in the log, the v$_{kick}$ distribution is χ^2-like with an average of 450 km/s and the rotational period at birth of neutron stars P_0 = 0.01 s. The total binary frequency (orbital period up to 10 years) at birth is 80%. As expected and confirmed by our computations, the HMXB$_1$ class never contribute significantly to the total X-ray luminosity of a starburst; we will not consider them further. The PNS model predicts the existence of WR+cc binaries of whom the majority are WR+black hole candidates. WR stars have a hydrostatic radius of the order of a solar radius and therefore, from condition (4), it can readily be checked that most of these binaries will become hard X-ray emitters when their orbital period P is smaller than about 0.4 days. In this case, the black hole is imbedded deep into the stellar wind of the WR star and a large fraction of the X-rays are absorbed (typically, the X-ray luminosity is reduced by a factor 1000 or more). The X-ray absorption in the WR wind in WR+neutron star binaries is obviously similar as in WR+black hole systems. Furthermore, a WR+neutron star binary that survived the previous spiral-in phase, must have had a OB+neutron star progenitor with very large period (see also Vanbeveren et al. 1998c). As a consequence, if a neutron star is formed as a rapid rotator, it may still be a rapid rotator when the OB star turns into a WR star. This rotation may prevent accretion and X-rays are not produced. Therefore,

WR+cc binaries hardly contribute to the overall X-ray luminosity of a starburst.

Note that this is consistent with the observational fact that within the Solar neighbourhood WR stars are absent among the optical components of the HMXBs. Cyg X-3 may be an exception, however, as argued by Mitra (1996) and by Vanbeveren et al. (1998b), the mass loser is probably not a normal population I WR star. Therefore, similar to the HMXB$_1$s, HMXB$_5$s will not be discussed any longer.

Fig. 1 illustrates the time variation of the X-ray luminosity in our standard starburst. Fig. 2 (resp. Fig. 3) is as Fig. 1 but with an average v$_{kick}$ = 150 km/s (resp. binary frequency = 10%). In Fig. 4 we compare the time variation of the X-ray luminosity of the YSNRs of the standard starburst with that of a model that assumes an initial neutron star rotation period of P_0 = 0.001 s. We decided to show total X-ray luminosities and did not consider particular passbands. All X-ray luminosities are escaping X-ray luminosities, i.e. they have intrinsic absorption included but no corrections for other absorption in the host galaxy or in the Milky Way. The stochastic character of the figures is due to the fact that, although the total number of stars in the burst is

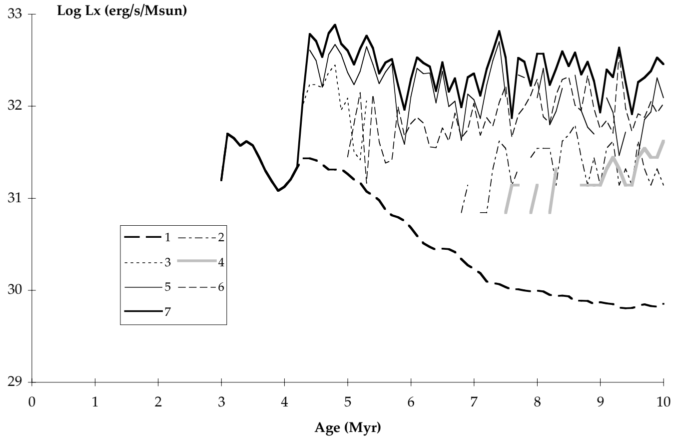

Fig. 1. X-ray luminosity (per unit stellar mass) as a function of time for our standard starburst (see text). The curves are labelled in the following way: 1) $HMXB_1$, 2) $HMXB_2$ with neutron star component, 3) $HMXB_2$ with black hole component, 4) $HMXB_3$ with neutron star component, 5) $HMXB_3$ with black hole component, 6) YSNRs, 7) the sum of all contributions.

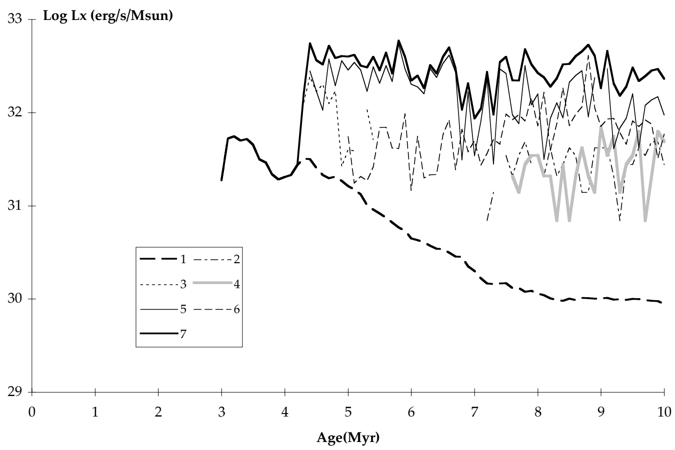

Fig. 2. Same as Fig. 1 but for an average kick velocity of neutron stars at birth of 150 km/s.

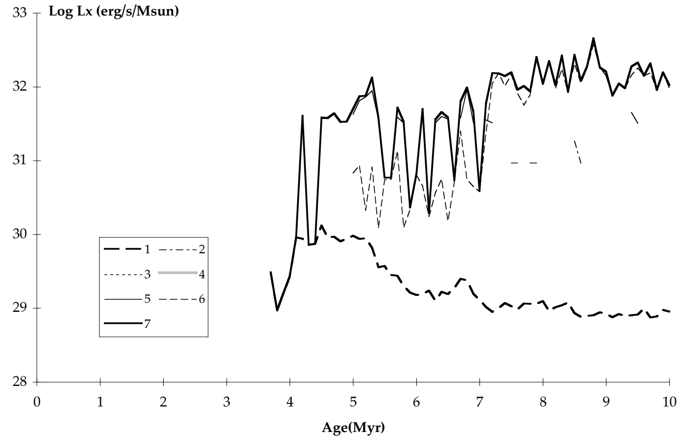

Fig. 3. Same as Fig. 1 but for a total binary frequency at birth of 10%.

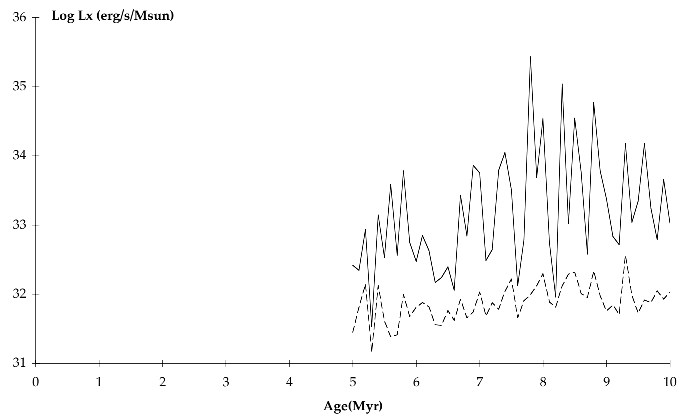

Fig. 4. X-ray luminosity (per unit stellar mass of the starburst) of YSNRs in the case they are born with a rotation period of 0.01 s (dashed line) and in the case they are born with a rotation period of 0.001 s (full line).

large, the number of bright YSNRs and/or HMXBs at a certain epoch is always of the order of a few. The luminosities are given divided by the total mass of massive stars in the burst. This total mass equals 29.6 million solar masses (resp. 22.2 million) for the standard starburst (resp. for a starburst with a 10% binary frequency). Since the results scale linearly with this total mass, they can easily be adapted for a burst with a different number of massive objects. After about 10 to 15 million years, a significant fraction of the OB+cc class are systems with an OB type star mass smaller than 20 $M_\odot$, and therefore a significant fraction of the HMXBs may be Be X-ray binaries. This is illustrated in Figs. 5, through 10 where we show the time variation of the number of O type stars, WR stars, YSNRs, and the brightest HMXBs for a standard starburst (we count all OB+cc binaries with $M_{OB} \leq 20\ M_\odot$ among the $HMXB_4$s, but remember that only a fraction of them will be real Be X-ray binaries). The unknown physics of the Be phenomenon is also the reason why we decided to show the time variation of the X-radiation of a starburst only up to 10 million years (Figs. 1-4). We conclude:

• When X-rays with energies larger than 2 keV are observed in a starburst, massive close binary evolution has played an important role in the evolution of the burst.

• When, initially, a significant fraction of all massive stars in a starburst are components of binaries, the observable X-ray phase (energies larger than 2 keV) of a starburst starts after 3-4 million years, i.e.

When X-rays are observed in a starburst with energies larger than 2 keV, the burst is at least 3-4 million years old.

• The YSNRs contribute to the total X-ray luminosity of a starburst only when most of the neutron stars are born with a rotation period ≤ 0.01 s.

• During the first 8 to 9 million years, the hard X-ray luminosity of starbursts comes from YSNRs and from HMXBs with a black hole component. This means that the X-ray spectrum of the starburst will be characterized by a kT $\approx$ 2 keV component due to YSNRs and a somewhat harder component due to black hole HMXBs. Notice however that our estimated number of HMXBs with a black hole component must be considered as

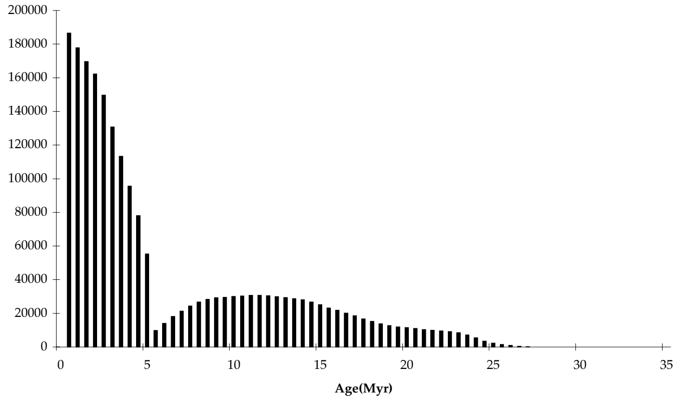

Fig. 5. The number of O type stars as a function of time in the standard starburst.

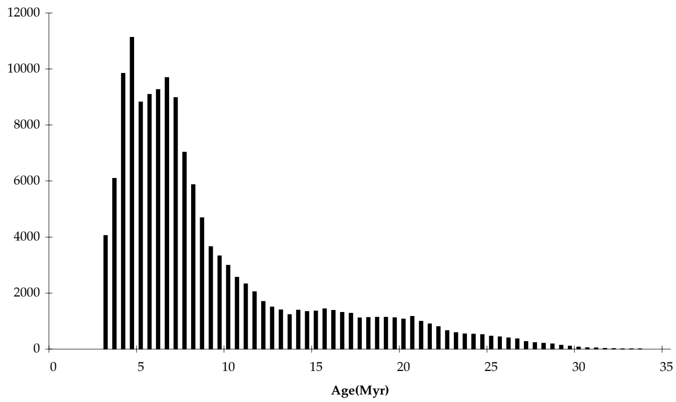

Fig. 6. The number of WR stars as a function of time in the standard starburst.

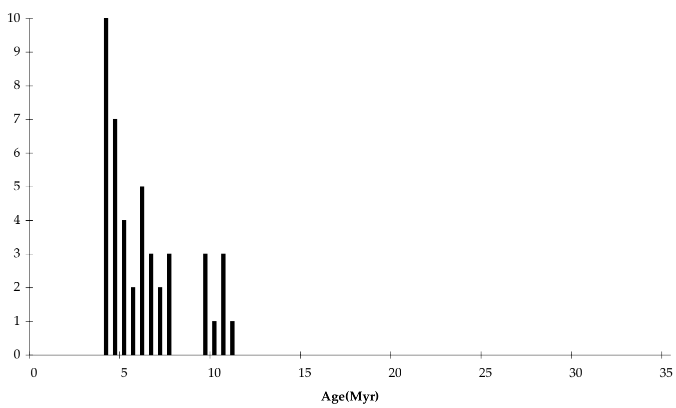

Fig. 7. The number of $HMXB_2$ + $HMXB_3$ with a black hole component as a function of time in the standard starburst. Most of them emit X-rays with a luminosity $L_x \geq 10^{39}$ erg/s.

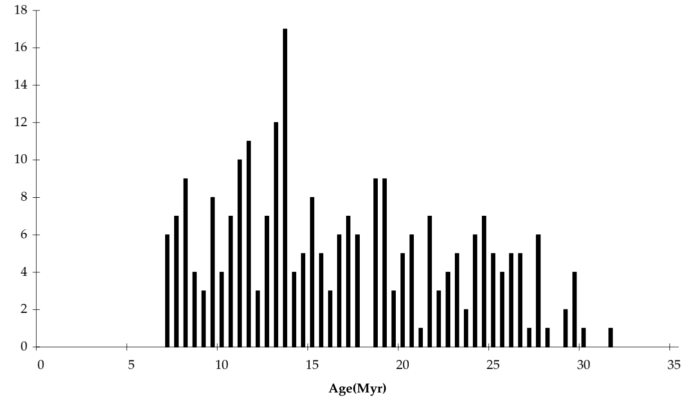

Fig. 8. The number of $HMXB_2$ + $HMXB_3$ with a neutron star component as a function of time in the standard starburst. Most of them emit X-rays with a luminosity $L_x \geq 10^{38}$ erg/s.

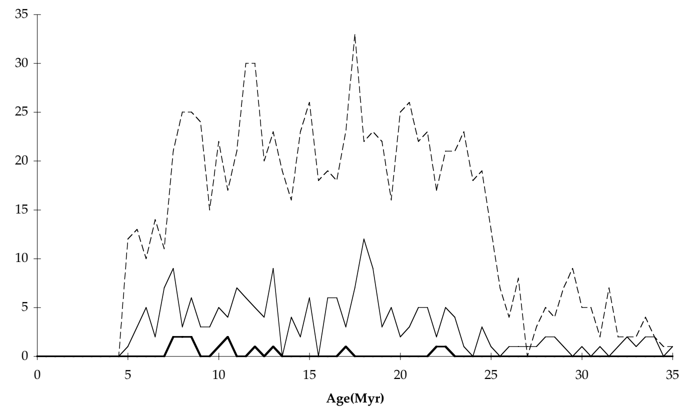

Fig. 9. The number of YSNRs as a function of time in the standard starburst. The bold full line (resp. thin full line and dashed line) are those which emit X-rays with $L_x \geq 10^{39}$ erg/s (resp. with $10^{38} \leq L_x \leq 10^{39}$ and with $10^{37} \leq L_x \leq 10^{38}$).

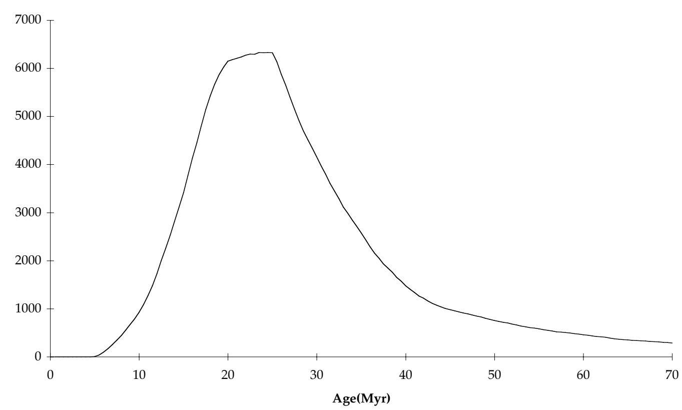

Fig. 10. The number of OB+cc binaries with $M_{OB} < 20\ M_\odot$ as a function of time in the standard starburst. A fraction of them will be visible as Be X-ray binaries.

an upper limit since we did not account for possible effects of a supernova explosion prior to black hole formation (see also Sect. 2).

• A starburst is expected to show a hard X-ray component with kT $\geq$ 15 keV due to the appearance of HMXBs with a neutron star component after about 8-9 million years. The spectral region $\geq$ 10 keV will be dominated by these HMXBs.

• When the disruption probability of a binary due to the supernova explosion of the primary decreases, the contribution of YSNRs to the total X-ray luminosity of a starburst becomes smaller during the first 7-8 million years. This is due to the

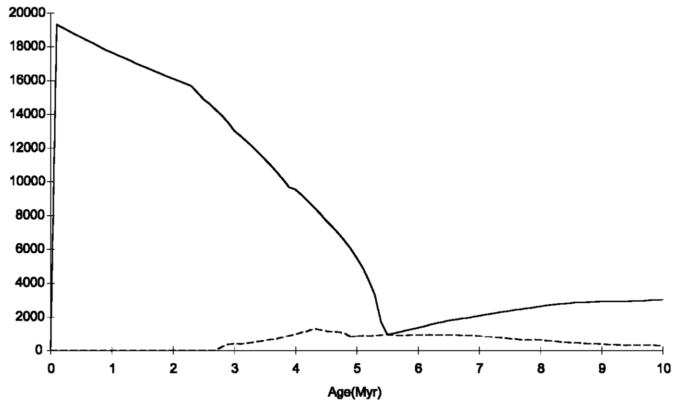

Fig. 11. The number of O type stars (full line) and WR stars (dashed line) as a function of time for a standard starburst that originally had $3 \cdot 10^4$ massive objects.

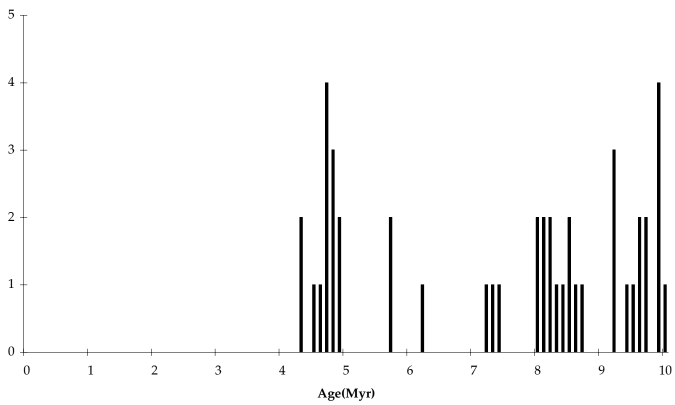

Fig. 12. The number of bright X-ray binaries as a function of time for a standard starburst that originally had $3 \cdot 10^4$ massive objects.

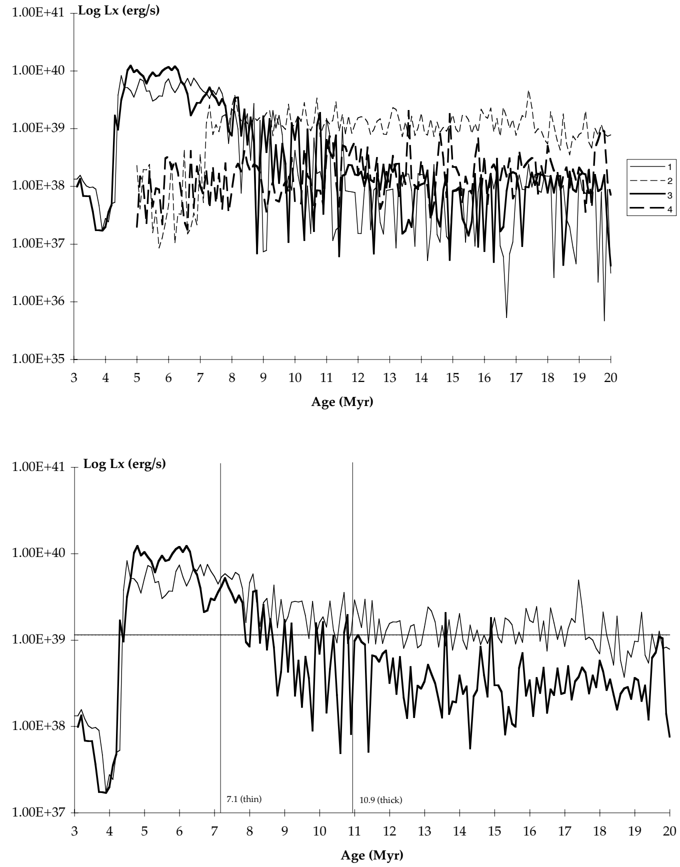

Fig. 13. The [2-10 keV] X-ray luminosity as a function of time for two starburst models that fit the observations of the starburst galaxy He2-10 (see text). The bottom figure shows the total luminosity (thick line corresponds to starburst 1, thin line to starburst 2) and in the top figure we distinguish the contribution to the X-ray luminosity of HMXBs and of YSNRs, i.e. curve 1 (resp. 2) describes the HMXBs (resp. YSNRs) of starburst 2 and curve 3 (resp. 4) describes the HMXBs (resp. YSNRs) of starburst 1.

fact that single stars with mass larger than about 25 $M_\odot$ do not produce YSNRs but collapse to form a black hole, whereas the formation of a single pulsar out of a binary becomes less probable.

• Up to about 7 million years, the X-rays coming from YSNRs are due to pulsars whose progenitors were binary components, which became single pulsars after disruption of the binary due to the supernova explosion. This means that when there are no massive binaries in a starburst, hard X-rays with luminosities $\geq 10^{39}$ erg/s are expected only after 7-8 million years. In this case YSNRs are the only agents, and therefore the X-ray spectrum should be rather soft (kT $\approx$ 2 keV, typical for YSNRs). This means that

When a starburst younger than approximately 7 million years emits hard X-rays, interacting massive close binaries must have been present initially in the burst.

• The theoretically predicted number of WR stars, O type stars, HMXBs and YSNRs obviously depends linearly on the total number of massive stars that are initially present in the burst. Figs. 11 and 12 illustrate the variation of the number of WR stars, O type stars and HMXBs for a standard starburst in which only $3 \cdot 10^4$ massive objects are initially present (this can be compared to Figs. 5 through 8 where the time variation is shown for a starburst which initially had 10 times more massive objects). As can be noticed, few HMXBs are expected as a function of time. The figure also illustrates the following statement:

Even when interacting binaries play an essential role in the evolution of a starburst, a WR galaxy does not always contain HMXBs.

• Depending on the physics of the Be phenomenon, a starburst galaxy can be classified as a HMXB galaxy up to an age of 50-70 million years, i.e. long after the disappearence of WR and O features, a starburst may still emit hard X-rays formed in HMXBs.

5. Application: the WR galaxy Henize 2-10

Table 1 summarizes the data, relevant for the present study, of the WR galaxy He2-10. We consider starburst models with a massive binary frequency at birth = 80% and 10%. The number of massive objects at birth is varied so that we obtain the correct number of WR and O type stars at the moment at which EW[H_β]

Table 1. Observational data of the WR galaxy He2-10, from Ohyama and Taniguchi (1999), Contini et al. (1999).

Z	0.008
EW(H_β) [Å]	23 ± 3
number of WN	1100 ± 500
number of WC	> 250
L_x [2-10keV]	$1.15 \cdot 10^{39}$
kT [keV]	≈ 4

$\approx$ 23 Å. The EW[H_β] is calculated as outlined by Van Bever et al. (1999). This resulted into two possibilities that fit the observations of He2-10, i.e. a burst that initially contains $5.1 \cdot 10^4$ (resp. $3 \cdot 10^5$) massive objects and a binary frequency of 80% (resp. 10%) = starburst 1 (resp. starburst 2). Starburst 1 (resp. starburst 2) fits He2-10 at an age of about 11 Myr (resp. 7 Myr). The [2-10 keV] X-ray luminosity is shown in Fig. 13 for the two models. For the YSNRs (resp. the HMXBs with a BH component and the HMXBs with a neutron star component) we use a Bremsstrahlungspectrum with kT = 2 keV (resp. 8 keV and 15 keV) to calculate the L_x[2-10 keV]. Although we still have to account for considerable uncertainties, observational and theoretical, starburst 1 gives the best total fit. We therefore conclude that

It is very hard (impossible?) to explain the WR and O star numbers and the X-ray data of the WR galaxy He2-10 without considering the influence on starburst evolution of a significant population of interacting massive close binaries.

It is clear that when the spectral resolution in the $\geq$ 2 keV hard X-ray band will improve and when it will become possible to observe individual point sources in a starburst we will be able to decide upon the influence of binaries on the evolution of active massive star forming regions.

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