THE CONTRIBUTION OF X-RAY BINARIES TO THE EVOLUTION OF LATE-TYPE GALAXIES: EVOLUTIONARY POPULATION SYNTHESIS SIMULATIONS

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ABSTRACT

X-ray studies of normal late-type galaxies have shown that non-nuclear X-ray emission is typically dominated by X-ray binaries and provides a useful measure of star formation activity. We have modeled the X-ray evolution of late-type galaxies over the \( \sim 14 \) Gyr of cosmic history, with an evolutionary population synthesis code developed by Hurley et al. Our calculations reveal a decrease in the X-ray luminosity-to-mass ratio \( L_X/M \) with time, in agreement with observations. We show that this decrease is a natural consequence of stellar and binary evolution and the mass accumulating process in galaxies. The X-ray-to-optical luminosity ratio \( L_X/L_B \) is found to be fairly constant (around \( \sim 10^{30} \text{ erg s}^{-1} L_B^{-1} \)) and insensitive to the star formation history in the galaxies. The nearly constant value of \( L_X/L_B \) is in conflict with the observed increase in \( L_X/L_B \) from \( z = 0 \) to 1.4. The discrepancy may be caused by intense obscured star formation activity that leads to a nonlinear relationship between X-ray and \textit{B}-band emission.

\textit{Key words:} binaries: close – galaxies: evolution – galaxies: general – stars: evolution – X-rays: binaries – X-rays: galaxies – X-rays: stars

\textit{Online-only material:} color figures

1. INTRODUCTION

The X-ray emission of a normal late-type galaxy (i.e., one without an active galactic nucleus) is often dominated by the integrated emission of the galactic X-ray binaries (XRBs; e.g., Fabbiano & White 2003; Colbert et al. 2004; Fabbiano 2006). Galactic XRBs can be classified into two distinct populations (Hartmann & van den Heuvel 1991): the short-lived (<10\textsuperscript{6} yr), high-mass X-ray binaries (HMXBs) and the long-lived (>10\textsuperscript{7} yr), low-mass X-ray binaries (LMXBs). The X-ray emission from HMXBs is usually regarded as trace current star formation (SP) because of their short lifetimes, while the X-ray emission from LMXBs is more closely related to the integrated stellar mass (Ptak et al. 2001; Ranalli et al. 2003; Grimm et al. 2003).

With the observations of galaxies at redshift \( z > 0.1 \), either from deep surveys by \textit{Chandra} and \textit{XMM-Newton} (see Brandt & Hasinger 2005, for a review) or from stacking analysis of distant galaxy fields (\( z \simeq 0.1–4 \); e.g., Brandt et al. 2001; Hornschemeier et al. 2002; Nandra et al. 2002; Georgakakis et al. 2003; Reddy & Steidel 2004; Laird et al. 2005, 2006; Lehmer et al. 2005, 2008), it has become possible to investigate the X-ray properties of normal galaxies at cosmologically significant redshifts (Hornschemeier et al. 2000, 2003; Alexander et al. 2002; Georgantopoulos et al. 2005; Georgakakis et al. 2006; Lehmer et al. 2006, 2007; Kim et al. 2006; Tzanavaris et al. 2006; Rosa-González et al. 2007).

Previous studies showed that the average X-ray luminosities \( L_X \) of normal late-type galaxies increase with redshift out to \( z \simeq 1.4–3 \), and evolve as \((1+z)^{1.5–3}\) over the redshift range \( z \simeq 0–1.4 \) for X-ray-detected normal galaxies (Norman et al. 2004; Ptak et al. 2007; Tzanavaris & Georgantopoulos 2008). Hornschemeier et al. (2002) performed a statistical X-ray study of spiral galaxies in the \textit{Hubble} Deep Field-North and its flanking fields using the \textit{Chandra} Deep Field-North 1 Ms data set and observed a factor of \( \sim 2–3 \) increase in the X-ray-to-optical luminosity ratio \( L_X/L_B \) from \( z = 0 \) to 1.4 for the \( L_B \)-selected galaxies. To improve the constraints on the X-ray evolution of late-type galaxies, Lehmer et al. (2008) studied for the first time how the X-ray properties evolve as a function of optical luminosity, stellar mass, and star formation rate (SFR) of the galaxies in the \textit{Chandra} Deep Fields North and South (Alexander et al. 2003; Giacconi et al. 2002). It was found that there is a significant increase (by a factor of about 5–10) in the X-ray-to-optical luminosity ratio \((L_X/L_B)\) and the X-ray-to-stellar mass ratio \((L_X/M)\) for the galaxy populations selected by \( L_B \) and \( M \), respectively, over the redshift range of \( z = 0–1.4 \). When analyzing the galaxy samples selected with SFR, these authors found that the X-ray luminosity-to-SFR ratio \((L_X/SFR)\) is constant over the entire redshift range for galaxies with SFR \( = 1–100 M_\odot \text{yr}^{-1} \) and that the SF activity (as traced by X-ray luminosity) per unit stellar mass in a given redshift bin increases with decreasing stellar mass over the redshift range \( z = 0.2–1 \), consistent with previous studies on how SF activity depends on stellar mass (Cowie et al. 1996;Juneau et al. 2005;Bundy et al. 2006;Noeske et al. 2007a, 2007b;Zheng et al. 2007). Finally, they extended their X-ray analyses to Lyman break galaxies at \( z \simeq 3 \) and estimated that the value of \( L_X/L_B \) at \( z = 3 \) is similar to that at \( z = 1.4 \).

X-ray emission of normal galaxies and its evolution have also been the subject of theoretical studies. Using a semi-empirical approach to link XRB lifetimes with a cosmological evolution of SFR, Ghosh & White (2001) discussed the imprints left by this cosmic SFR on the evolution of X-ray luminosities \( L_X \) of normal galaxies. They showed that the evolving SFRs can strongly affect the integrated galactic X-ray emission, with the possibility of significant evolution of the X-ray luminosities even within relatively low redshifts \( z < 1 \) (see also White & Ghosh 1998). Eracleous et al. (2004) simulated the evolution of X-ray luminosities of XRBs after a burst of SF with a
duration of 20 Myr with a population synthesis method and found that the 2–10 keV luminosity reaches a maximum after approximately 20 Myr, and the X-ray luminous phase can be sustained for a period of hundreds of Myr. The results were shown to be insensitive to the initial mass function (IMF) and the average mass ratio between accreting and donor stars. However, a comprehensive study on the evolution of X-ray populations in galaxies and their relation with other properties is still lacking.

In the present work, we use an evolutionary population synthesis (EPS) code to calculate the X-ray luminosity of XRBs and its evolution in a normal late-type galaxy over the cosmic history. Meanwhile, we calculate the optical luminosity and the galactic mass contributed by stellar populations. The objective of this study is to investigate the X-ray evolution of late-type galaxy populations and its dependence on the physical properties of galaxies (e.g., optical luminosity, stellar mass, and mass-to-light ratio) and on the star formation history (SFH), from a theoretical point of view. We will also examine how the key light ratio) and on the star formation history (SFH), from a comprehensive study on the evolution of X-ray populations in galaxies, and their relation with other properties is still lacking.

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### 2. MODELS

#### 2.1. Assumptions and Input Parameters

We used the EPS code developed by Hurley et al. (2000, 2002) and updated by Liu & Li (2007, see Appendix A in the paper) and Zuo et al. (2008) to calculate the X-ray luminosity of XRBs, the optical luminosity of XRBs, and the stellar mass \( M \) of the host galaxy, as well as their evolution. The values of the adopted parameters are the same as the default ones in Hurley et al. (2002) if not mentioned otherwise.

Previous works (Shapley et al. 2001; Persic & Rephaeli 2007; Lehmer et al. 2008) have already shown that the galactic X-ray emission is closely related to the SF activity. So we constructed three cases, i.e., constant SF; starburst SF; and cosmic SF, to examine their effect. We also examined several key parameters, such as the IMF, CE efficiency parameter, the binary fraction, and metallicity (listed in Table 1 and discussed below), to explore their influence on the X-ray evolution of the galaxies.

#### 1. Constant star formation case

In this case, we adopt a constant SFR \( = 0.25 \text{ M}_\odot \text{ yr}^{-1} \) for stars more massive than \( 5 \text{ M}_\odot \) derived by Grimm et al. (2003) in our galaxy and take the star formation duration (SFD) to be 14 Gyr. For each model, we evolve \( 10^6 \) primordial binary systems, with the same grid of initial parameters (i.e., primary and secondary mass, orbital separation) as Hurley et al. (2002). We also evolve \( 10^6 \) primordial single stars, with initial mass log-normally spaced between \( 0.1 \text{ M}_\odot \) and \( 80 \text{ M}_\odot \). In our basic model (i.e., model M1), we assume the binary fraction \( f \) to be 0.5 and evolve each binary and single star on the grid. In the following, we describe the assumptions and input parameters in our basic model.

In order to be in parallel with Lehmer et al. (2008), we take the IMF of Kroupa (2001, hereafter KROUPA01) for the mass \( M_1 \) distribution of the primary stars. For the secondary stars (of mass \( M_2 \)) and binary orbit, we assume a uniform distribution between 0 and 1 for the mass ratio \( q \equiv M_2/M_1 \) and a uniform distribution for the logarithm of the orbital separation \( ln a \) (Hurley et al. 2002). We fix the metallicity to be solar over the lifetime of the simulated galaxy.

We assume that any system entering Roche-lobe overflow becomes circularized and synchronized by tidal interaction between the binary components (Belczynski et al. 2008). An important parameter in the binary evolution is the CE efficiency parameter \( \alpha_{CE} \) (Paczynski 1976; Iben & Livio 1993), which describes the efficiency of converting orbital energy into the kinetic energy ejecting the envelope (see Section 2.1.1 in Zuo & Li 2010, for details). It can often reduce the orbital separation of the surviving binaries by a factor of \( \sim 100 \), resulting in different outcomes of binary systems. In our basic model, we adopt \( \alpha_{CE} = 0.3 \), which can best model the luminosity function of the galaxy (Zuo et al. 2008).

We also construct several other models (listed in Table 1) by varying the key input parameters described as follows.

1. As stated above, variations of the CE parameter can considerably change the relative numbers of XRBs. However reliable values of \( \alpha_{CE} \) are difficult to estimate due to lack of understanding of the processes involved, although in literature it is in the range from \(-0.1 \) to \( \sim 3.0 \) (e.g., Taam & Bodenheimer 1989; Tutukov & Yungelson 1993; Podsiadlowski et al. 2003). Here we also adopt \( \alpha_{CE} = 1.0 \) (model M2) to examine its effect.

2. The IMF determines the percentage of high-mass stars, consequently the number of XRBs produced, and the X-ray luminosity of the galaxy. So, we also make use of the IMF of Kroupa et al. (1993, hereafter KTG, model M5), which is much steeper in the high-mass end than in KROUPA01.

| SF Case | Model | \( \alpha_{CE} \) | \( q(q) \) | IMF | \( f \) | \( Z \) (Z\(_\odot\)) | SFD (Myr) |
|--------|-------|-----------------|-------------|-----|-----|-------------|----------|
| Constant SF | M1 | 0.3 | \( q^0 \) | KROUPA01 | 0.5 | 1.0 | 14000 |
|          | M2 | 1.0 | \( q^0 \) | KROUPA01 | 0.5 | 1.0 | 14000 |
|          | M3 | 0.3 | \( q^0 \) | KROUPA01 | 0.5 | 1.0 | 14000 |
|          | M4 | 0.3 | \( q^0 \) | KROUPA01 | 0.8 | 1.0 | 14000 |
|          | M5 | 0.3 | \( q^0 \) | KTG93 | 0.5 | 1.0 | 14000 |
|          | M6 | 0.3 | \( q^0 \) | KROUPA01 | 0.5 | 1.5 | 14000 |
|          | M7 | 0.3 | \( q^0 \) | KROUPA01 | 0.5 | 0.5 | 14000 |
|          | M8 | 0.3 | \( q^0 \) | KROUPA01 | 0.5 | 0.1 | 14000 |
|          | M9 | 0.3 | \( q^0 \) | KROUPA01 | 0.5 | 0.02 | 14000 |
| Starburst SF | M10 | 0.3 | \( q^0 \) | KROUPA01 | 0.5 | 1.0 | 100 |
|          | M11 | 0.3 | \( q^0 \) | KROUPA01 | 0.5 | 1.0 | 20 |
|          | M12 | 0.3 | \( q^0 \) | KROUPA01 | 0.5 | 0.02 | 100 |

Notes. Here, \( \alpha_{CE} \) is the CE efficiency parameter, \( q \) is the initial mass ratio, IMF is the initial mass function, \( f \) is the binary fraction, \( Z \) is the metallicity in solar units, and SFD is the duration of SF in the simulated galaxy.

In order to be in parallel with Lehmer et al. (2008), we take the IMF of Kroupa (2001, hereafter KROUPA01) for the mass \( M_1 \) distribution of the primary stars. For the secondary stars (of mass \( M_2 \)) and binary orbit, we assume a uniform distribution between 0 and 1 for the mass ratio \( q \equiv M_2/M_1 \) and a uniform distribution for the logarithm of the orbital separation \( ln a \) (Hurley et al. 2002). We fix the metallicity to be solar over the lifetime of the simulated galaxy.
3. Surveys of M dwarfs within 20 pc from the Sun indicate that the binary fraction $f$ may be a function of stellar spectral types (Fischer & Marcy 1992), for example, $f > 0.5$ for G stars and $f > 0.6$ for massive O/B stars in the Cygnus OB2 association (Lada 2006; Kobulnicky & Fryer 2007). So, we also adopt $f = 0.8$ (model M4) for comparison.

4. Observations of the hosts of XRBs revealed that XRBs, especially ultra-luminous X-ray sources, may prefer to occur in galaxies with low metallicities (Mapelli et al. 2009). So, we vary the metallicity to examine its effect on the X-ray luminosity evolution by taking $Z = 1.5 Z_\odot$ (model M6), $0.5 Z_\odot$ (model M7), $0.1 Z_\odot$ (model M8), and $0.02 Z_\odot$ (model M9), in order to compare with our basic model (M1 with $Z_\odot$). The other parameters in these models are the same as the ones in our basic model.

2. Starburst star formation case

In galaxies like our own Galaxy, continuous SF processes may last for several Gyr, but this is not the case for starburst galaxies. For example, the Antennae galaxies may have experienced SF for the last several hundred Myr with an enhanced SFR of $\Sigma_\text{SFR} = 7.1 M_\odot \text{yr}^{-1}$ Barnes (1988; Mihos et al. 1993). To reveal the effect of SFH, we take the following combinations of SFR and metallicities: 100 $M_\odot/ Z_\odot$ (model M10), 20 $M_\odot/ Z_\odot$ (model M11), and 100 $M_\odot/ 0.02 Z_\odot$ (model M12). We assume that the SF is quenched after the SFD time and set other parameters to be the same as in our basic model.

3. Cosmic star formation case

With improved observations of SF processes, cosmic SF can be constrained quite tightly within $30\%$–$50\%$ up to $z \sim 1$ and within a factor of $3$ up to $z = 6$ (Hopkins 2004), which makes it possible to investigate the cosmic X-ray evolution of galaxies. Here we adopt the derived expression of the SFH in Hopkins & Beacom (2006),

$$\rho_{\text{SF}}(z) \propto \begin{cases} (1+z)^{3.44} & z \leq 0.97 \\ (1+z)^{-0.26} & 0.97 \leq z \leq 4.48 \\ (1+z)^{-7.8} & 4.48 < z, \end{cases}$$

and scale the SFR at redshift $z = 0$ to be the same as that of our Galaxy. Moreover, it is known that the cosmic metallicity also evolves strongly with redshift, and galaxies at higher redshift tend to have lower metallicities (Pettini et al. 1999; Prochaska et al. 2003; Rao et al. 2003; Kobulnicky & Kewley 2004; Kulkarni et al. 2005, 2007; Savaglio et al. 2005, 2009; Savaglio 2006; Podsiadlowski 2007; Péroux et al. 2007). So, we adopt an empirical equation $Z/ Z_\odot \propto 10^{-0.8z}$ (Langer & Norman 2006) for metallicity evolution with $\gamma = 0.15$ (Kewley & Kobulnicky 2007). We also vary the IMF to a steeper one (KTG93) and a shallower one (Baldry & Glazebrook 2003, BG03 for short) to examine its effect in this case. The other parameters are the same as in our basic model.

2.2. X-ray Luminosity and Source Type

We adopt the same procedure to calculate the 0.5–8 keV X-ray luminosities of different XRB populations as in Zuo & Li (2010). Mass transfer in XRBs occurs via either Roche-lobe overflow or capture of the wind material from the donor star. We use the classical Bondi & Hoyle (1944) formula to calculate the wind accretion rate of the compact stars. In the case of Roche-lobe overflow, mass is transferred to the accreting star by way of an accretion disk. It is known that accretion disks in LMXBs are subject to thermal instability if the accretion rate is sufficiently low (van Paradijs 1996). We discriminate transient and persistent LMXBs according to the criteria of van Paradijs (1996) for main sequence (MS) and red giant donors and of Ivanova & Kalogera (2006) for white dwarf (WD) donors, respectively. The simulated X-ray luminosity is described as follows,

$$L_{\text{X,0.5–8 keV}} = \begin{cases} \eta_{\text{bol}} L_{\text{transients}} L_{\text{Edd}} \\ \eta_{\text{bol}} \min(L_{\text{bol}}, \eta_{\text{Edd}} L_{\text{Edd}}) \end{cases}$$

where the bolometric accretion luminosity $L_{\text{bol}} \simeq 0.1 \dot{M}_{\text{acc}} c^2$ (where $\dot{M}_{\text{acc}}$ is the accretion rate and $c$ is the velocity of light), the critical Eddington luminosity $L_{\text{Edd}} \simeq 4\pi G m_1 m_p c/\sigma_T = 1.3 \times 10^{38} m_1 \text{ erg s}^{-1}$ (where $\sigma_T$ is the Thomson cross section, $m_p$ is the proton mass, $G$ is the gravitational constant, and $m_1$ is the accretor mass in units of the solar mass), and $\eta_{\text{Edd}}$ is the factor to allow super-Eddington luminosities, taken to be 5 (Ohsuga et al. 2002; Begelman 2002). To transform the bolometric luminosity into the 0.5–8 keV X-ray luminosity, a bolometric correction factor $\eta_{\text{bol}}$ is introduced (Belczynski & Taam 2004). Generally, its value is $0.1–0.5$ for different types of XRBs; here we adopt $\eta_{\text{bol}} \simeq 0.1$. For transient sources, the X-ray luminosity during outbursts should be larger than the long-term one by a factor $\eta_{\text{out}}$. We take $\eta_{\text{out}} = 0.1$ and 1 for the short- and long-period systems, and the critical periods are adopted to be 1 day for neutron star (NS) transients and 10 hr for black hole (BH) transients, respectively (Chen et al. 1997; García et al. 2003; Belczynski et al. 2008).

2.3. Optical Luminosity $L_B$ and Stellar Mass of the Galaxy

The optical luminosity $L_B$ of a galaxy is mostly from normal stars (both binary and single stars). Assume that the stellar radiation can be reasonably approximated as a blackbody, the $B$-band luminosity of a star is calculated with $L_B = \int_{f_{\text{bol}}}^{f_{\text{Edd}}} \rho_B \frac{\lambda}{c} \frac{d\lambda}{d\lambda}$, where $L$ is the total thermal luminosity of the star, and the radiative intensity $I_\lambda = \frac{\rho_B \lambda}{c} \frac{d\lambda}{d\lambda}$, where $h$ is the Planck constant, $k$ is the Boltzmann constant, and $T_{\text{eff}}$ is the effective temperature.

We also examine the contribution of optical luminosity from accretion disks in XRBs, resulting from the reprocessing of X-ray photons. We calculate the optical luminosity $L_B$ from the accretion disk in BH XRBs following Madhusudhan et al. (2008), adopting the same temperature profile (i.e., their Equation (4)) to describe the effective temperature in the disk. For NS XRBs, we find similar results as BH XRBs. Our calculation reveals that optical radiation from accretion disks in XRBs is negligible compared to the overall stellar optical luminosity.

The stellar mass here is the sum of the masses of currently living stars and does not include the contribution from compact stars (WDs, NSs, and BHs), in order to be in parallel with Lehmer et al. (2008), where they used the rest-frame $B-V$ color and K-band luminosity to estimate the masses of the galaxies.
Zuo & Li

Figure 1. Evolution of (a) the X-ray luminosity ($L_X$), (b) the optical luminosity ($L_B$), (c) the X-ray luminosity-to-stellar mass ratio ($L_X/M$), (d) the X-ray-to-$B$-band luminosity ratio ($L_X/L_B$), (e) the $L_X/M/L_B$ ratio, and (f) the stellar-mass-to-$B$-band luminosity ratio ($M/L_B$) with time in the constant SF case. Here the metallicity is $Z_{\odot}$. We assume that the secondary mass distribution follows the power-law $P(q) = q^\alpha$ and the binary fraction is $f$. The left panels show the results in the basic model with $\alpha_{CE} = 0.3$, $\alpha = 0$, $f = 0.5$, and the KROUPA01 IMF. The other models from left to right are with $\alpha_{CE} = 1.0$, $\alpha = 1$, $f = 0.8$, and the KTG93 IMF, respectively.

(A color version of this figure is available in the online journal.)

For X-ray luminosities $L_X$ (Figure 1(a)) we plot the contributions from HMXBs and LMXBs with dotted and dashed lines, respectively. The X-ray luminosity of HMXBs rises rapidly shortly after the first SF and remains nearly constant afterward, because of continuous, constant SF. LMXBs take a much longer time to form, and their number is correlated with the total star mass, resulting in a long-term increasing trend in X-ray luminosity with time. The position of the crossing point of the two lines depends most strongly on the CE parameter $\alpha_{CE}$ (larger $\alpha_{CE}$ results in more LMXBs).

The optical luminosity $L_B$ (Figure 1(b)) is contributed by the primary stars (dotted line) and secondary stars (dashed line) in binaries, and by single stars (long-dashed line). When the fraction of binaries is larger (model M4), more XRBs are produced, leading to larger $L_X$, and hence larger $L_X/M$, $L_X/L_B$ and $L_X/(M/L_B)$ ratios compared with those in the basic model.

The steeper end of IMF (i.e., model M5) implies a smaller number of massive stars (and smaller $L_B$), resulting in fewer compact objects and smaller $L_X$. So the $L_X/M$ and $L_X/(M/L_B)$ ratios in this case are smaller than those in models M1–M4.

The $L_X/M$ ratio (Figure 1(c)) has a clear decreasing trend after the age of tens of Myr. Observationally, this phenomenon was regarded as evidence that lower mass galaxies appear to have higher specific SFRs than massive ones (Brinchmann et al. 2004; Bauer et al. 2005; Noeske et al. 2007a; Feulner et al. 2005; Zheng et al. 2007). Our results show that the decrease
of $L_X/M$ is a natural consequence of XRB evolution and the stellar mass accumulating process in galaxies—the stellar mass always steadily increases while the X-ray luminosity changes little during most of the evolution.

The $L_X/L_B$ ratio (Figure 1(d)), similar to $L_X$, rises in the first several Myr, then remains nearly constant afterward. The flattening values are all around $10^{39}$ erg s$^{-1}$L$_{\odot}^{-1}$, but have severalfold changes among different models. They are caused by the diversity in the percentages of both total massive stars and massive stars in binaries, which determine $L_B$ and $L_X$, respectively. The ratios of the peak values of log($L_X/L_B$) are roughly 1 : 1 : 0.5 : 1.5 : 1 from models M1 to M5.

Figure 2 shows the cumulative X-ray luminosity functions (XLFs) of HMXBs (dotted line) and LMXBs (dashed line) in the top panels. The parameters are the same as in Figure 1. Note that HMXBs and LMXBs dominate at relatively high ($>10^{39}$ erg s$^{-1}$) and low ($<10^{39}$ erg s$^{-1}$) luminosity ends, respectively. We also show the detailed components of XRBs which contribute the total X-ray luminosity separately in the middle (HMXBs) and bottom (LMXBs) panels of Figure 2. The dotted, dashed, dash-dotted, and dash-dot-dotted lines represent persistent BH XRBs (BHp), transient BH XRBs (BHt), persistent NS XRBs (NSp), and transient NS XRBs (NSt), respectively. It is seen that for HMXBs persistent BH XRBs contribute most to the XLF; for LMXBs, BH-XRBs (both BHp and BHt) dominate the high-luminosity end of XLF, while in the low-luminosity end transient NS-XRBs play a more important role.

Figure 3 shows the evolution of $L_X$, $L_B$, $L_X/M$, $L_X/L_B$, $L_X/(M/L_B)$, and $M/L_B$ with metallicities taken to be $1.5 Z_{\odot}$, $Z_{\odot}$, $0.5 Z_{\odot}$, $0.1 Z_{\odot}$, and $0.02 Z_{\odot}$, corresponding to models M6, M1, M7, M8, and M9 from left to right, respectively. Note that both $L_X$ and $L_B$ have a roughly increasing trend with decreasing metallicity. The values of $L_X/M$ and $L_X/L_B$ are comparable among different models. The values of the peak values are $\sim 1 : 1 : 0.7 : 1 : 2$ for log($L_X/M$) and $\sim 1 : 1 : 0.5 : 1 : 1$ for log($L_X/L_B$). The corresponding cumulative XLF is shown in Figure 4.

### 3.2. Starburst Star Formation Case

We present the evolution of $L_X$, $L_B$, $L_X/M$, $L_X/L_B$, $L_X/(M/L_B)$, and $M/L_B$ in the starburst case in Figure 5. Here the metallicity and SFD are assumed to be $Z_{\odot}/100$ Myr (left), $Z_{\odot}/20$ Myr (middle), and $0.02 Z_{\odot}/100$ Myr (right). It is seen that the X-ray luminosity $L_X$ (Figure 5(a)) rises to its peak within the SF episodes (peaked at the age of about 100 Myr for models M10 and M12, and at about 20 Myr for model M11), then decreases with time, lasting at least several $10^8$ yr with $L_X > 10^{37}$ erg s$^{-1}$. Note that the small serration emerging in late evolution is mainly caused by LMXBs (i.e., X-ray transient outbursts due to thermal instability in the accretion disks). The optical luminosity $L_B$ (Figure 5(b)) decreases sharply when the SF process stops, since massive stars contribute significantly during the starburst episode. The $L_X/M$ (Figure 5(c)) and also $L_X/(M/L_B)$, Figure 5(e)) ratio roughly follows the trend of $L_X$. However the slope in this case is much steeper than in Figures 1 and 3, because of the rapid decay of the X-ray luminosity. The $L_X/L_B$ (Figure 5(d)) ratio in the three models is all comparable with those in Figures 1 and 3, implying that it is intrinsically not sensitive to the SFH of the galaxies.

### 3.3. Cosmic Star Formation Case

Figure 6 shows the evolution of $L_X$, $L_B$, $L_X/M$, $L_X/L_B$, $L_X/(M/L_B)$, and $M/L_B$ with time (left) and redshift $z$ (right), with a cosmic SFH (from Hopkins & Beacom 2006) and a cosmic metallicity evolution history (from Langer & Norman 2006) taken into account. Note that the X-ray luminosity $L_X$ is mainly dominated by HMXBs in this case over the whole cosmic history because of the enhanced SFR with increasing redshift as a whole. This is comparable with the work of
Lehmer et al. (2008), where they found that LMXBs on average play a fairly small role in the X-ray emission. The $L_X/M$ ratio has a decreasing trend after the age of tens of Myr (or increases with $z$), similar to the constant/burst SF cases. This also confirms our previous conclusion that the decrease of $L_X/M$ with time results from XRB evolution and stellar mass growth in the galaxies. The $L_X/L_B$ ratio rises rapidly in the first several Myr, then stays around $10^{30}$ erg s$^{-1}$ L$_{B,\odot}^{-1}$ afterward, similar to the constant/burst SF cases, indicating that the $L_X/L_B$ ratio is not sensitive to the SFH in the galaxies.

To compare the theoretical predictions with observations, we replot Figures 6(c) and 6(d) in Figures 7(a) and 7(b), with redshift $z$ ranging from 0 to 2.0. The solid, dotted, and dashed lines represent the modeled results with IMFs of KROUPA01, Kroupa et al. (1993, KTG93), and Baldry & Glazebrook (2003, BG03), respectively. The observational data of log($L_X/M$) and log($L_X/L_B$) are taken from Shapley et al. (2001, S01) for normal late-type galaxies in the local universe (open symbols), Lehmer et al. (2008, L08) with the stellar masses $10^{10} < M/M_\odot < 10^{11.2}$ (squares, Figure 7(a)), $B$-band luminosities $10^{10.5} < L_B/L_{B,\odot} < 10^{11.3}$ (filled circles, Figure 7(b)) and $10^{10.0} < L_B/L_{B,\odot} < 10^{10.5}$ (filled squares, Figure 7(b)), and Zheng et al. (2007, Z07) with $10^{10.0} < M/M_\odot < 10^{10.5}$ (diamonds, Figure 7(a)). In these samples, the stellar masses...
are roughly comparable with our simulated ones. To convert the SSFR into $L_X/M$, we have made use of the local $L_X$–SFR relation derived by Persic & Rephaeli (2007).

It seems that our simulated $\log(L_X/M)$ versus $z$ relations match the observations quite well. Our calculations reveal that the modeled stellar masses are similar to each other within 10% when we use different types of IMFs, suggesting that the variation of the $L_X/M$ ratio is mainly caused by the differences in X-ray luminosity $L_X$. The values of $L_X/M$ can vary by a factor of $\sim 7$ between models (KTG93 versus BG03), as seen in Figure 7(a).

The nearly constant values of $L_X/L_B$ in Figure 7(b) seem to not properly match the observed increase in $L_X/L_B$ with $z$ (Hornschemeier et al. 2002; Lehmer et al. 2008). The discrepancy originates from the fact that in our simulations we have roughly $L_X \propto L_B$, giving a flat $L_X/L_B - z$ relation, while observationally it was found that $L_X \propto L_B^{1.5}$ (Shapley et al. 2001; Fabbiano & Shapley 2002; Lehmer et al. 2008), leading to increasing $L_X/L_B$ with $z$. Fabbiano & Shapley (2002) have discussed the X-ray-$B$-band luminosity correlation and suggested that the nonlinear power-law dependency in disk galaxies is likely to be due to extinction in dusty star-forming regions, which attenuates light from the $B$ band more effectively than it does in the X-ray band. This means that the intrinsic $B$-band luminosity calculated here is generally larger than the measured one, which suffers local extinction in the galaxies. Supporting evidence for this hypothesis also comes from the strong positive correlations between $L_X/L_B$ and the ultraviolet dust-extinction measure $(L_{IR} + L_{UV})/L_{UV}$, and the correlation between $L_X/L_B$ and IR color (Lehmer et al. 2008). Thus, if the increase in $L_X/L_B$ with $z$ in the late-type galaxies is due to an increase in their SF activity (Fabbiano & Shapley 2002; Lehmer et al. 2008), our results are compatible with the observational data at least qualitatively.

Figure 8 shows the corresponding cumulative XLFs. In general, they are similar to those in the case of constant SF.

Our simulations are obviously subject to many uncertainties. For current population synthesis investigations, it is difficult to tell confidently which parameter combinations are the best or most realistic by comparison with observations, since there are many uncertainties in the (both explicit and implicit) assumptions and input parameters, and simplifications in the treatment of the detailed evolutionary processes. For example, the simulated X-ray luminosity $L_X$ depends on the adopted values of several parameters, such as the bolometric correction factor $\eta_{bol}$, the CE efficiency parameter, and so on, which may alter its value severalfold. This further affects the values of $L_X/M$ and $L_X/L_B$ since the stellar mass $M$ and the optical luminosity $L_B$ are not sensitive to these parameters. Despite these limitations, it has become possible to investigate the overall evolution of stars in galaxies with population synthesis and to draw useful information by comparing theoretical predictions with observations.

4. SUMMARY

We have used an EPS code to calculate the X-ray evolution of late-type galaxies, to investigate the relations between the X-ray luminosity and other physical properties (i.e., optical luminosity, stellar mass, and SFH) of the galaxies, and how these relations are influenced by the input parameters of SF and evolution (e.g., SFH, IMF, metallicity, CE efficiency, etc.). The results are compared with multi-wavelength analyses and observations of late-type galaxies (Shapley et al. 2001; Zheng et al. 2007; Lehmer et al. 2008). In different cases of SF, we find a common feature of decreasing X-ray luminosity-to-mass ratio $L_X/M$ with time, in agreement with observations (Figure 7(a)). We show that the decrease of $L_X/M$ results from slow evolution of $L_X$ of XRBs and the stellar mass accumulation with time in galaxies, without requiring that lower mass galaxies have higher SSFR than more massive ones as suggested before (Brinchmann et al. 2004; Bauer et al. 2005; Noeske et al. 2007a; Feulner et al. 2005; Zheng et al. 2007). The $L_X/L_B$ ratios in all cases

| $L_X/L_B$ | $L_X/M$ | $L_X/L_B$ | $L_X/M$ | $L_X/L_B$ | $L_X/M$ |
|-----------|---------|-----------|---------|-----------|---------|
| 0.1       | 1.1     | 0.1       | 1.1     | 0.1       | 1.1     |
| 0.2       | 2.2     | 0.2       | 2.2     | 0.2       | 2.2     |
| 0.3       | 3.3     | 0.3       | 3.3     | 0.3       | 3.3     |
| 0.4       | 4.4     | 0.4       | 4.4     | 0.4       | 4.4     |
| 0.5       | 5.5     | 0.5       | 5.5     | 0.5       | 5.5     |

(A color version of this figure is available in the online journal.)
Figure 5. $L_X$, $L_B$, $L_X/M$, $L_X/L_B$, $L_X/(M/L_B)$, $M/L_B$ evolution with time in the starburst case. Here the metallicities and SFH are $Z_\odot/100$ Myr (left, M10), $Z_\odot/20$ Myr (middle, M11), and 0.02 $Z_\odot/100$ Myr (right, M12), respectively.

(A color version of this figure is available in the online journal.)
rise rapidly in the first $\sim 10^8$ yr to $\sim 10^{30}$ erg s$^{-1}$ L$_{B,\odot}^{-1}$, then stay nearly constant afterward for a given model, and are not sensitive to the SFH details in the galaxies (see Figure 7(b)). This seems to be in conflict with the observed increase in $L_X/L_B$ with $z$ (Hornschemeier et al. 2002; Fabbianno & Shapley 2002; Lehmer et al. 2008). The discrepancy may be due to different obscured SF activities in galaxies at higher redshifts (Fabbianno & Shapley 2002; Lehmer et al. 2008). This will be investigated by future high-resolution X-ray and optical observations of galaxies at high redshifts.

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Figure 7. Same as panels (c) and (d) in Figure 6 but enlarged with $z = 0–2$ for comparison with observations. The solid, dotted, and dashed lines represent modeled results with IMFs of Kroupa (2001, KROUPA01), Kroupa et al. (1993, KTG93), and Baldry & Glazebrook (2003, BG03), respectively. Also shown are the measured values of $\log (L_{X}/M)$ (left panel) selected by $M (10^{10.1} < M / M_\odot < 10^{11.2}$, squares) and $\log (L_{X}/R)$ (right panel) selected by $L_{X} (10^{10.5} < L_{X}/L_\odot < 10^{11.5}$, filled circles; $10^{10} < L_{X}/L_\odot < 10^{10.5}$, filled squares), respectively, for stacked normal late-type galaxy samples derived by Lehmer et al. (2008, L08). The symbols are the same as in Figure 10 of L08. We converted the SSFR to $L_{X}/M$ in Zheng et al. (2007, Z07) samples of the corresponding stellar mass bin ($10^{10} < M / M_\odot < 10^{10.5}$, diamonds), using the local $L_{X}$–SFR relation derived by Persic & Rephaeli (2007). The data for normal late-type galaxies in the local universe (open symbols) are from the Shapley et al. (2001, S01) samples.

(A color version of this figure is available in the online journal.)

Figure 8. Cumulative X-ray luminosity function (left: H+L; middle: H; right: L). Here we have assumed a cosmic SFH (from Hopkins & Beacom2006) and a cosmic metallicity evolution history (from Langer & Norman 2006).

(A color version of this figure is available in the online journal.)

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