LUMINOUS FUNCTIONS OF X-RAY BINARIES AND THEIR DYNAMICAL HISTORY OF THE HOST GALAXIES

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Abstract

The X-ray sources observed in nearby galaxies show brightness distributions (log(N(> S))–log(S) curves) which can be described as single or broken power laws. Single power-law distributions are often found for sources in galaxies with vigorous ongoing star-formation activity, while broken power laws are found in elliptical galaxies and in bulges of spiral galaxies. The luminosity break can be caused by a population of X-ray binaries which contain a neutron star accreting at the Eddington limit or by aging of the X-ray binary population. We show that a simple birth-death model can reproduce single and broken power-law log(N(> S))–log(S) curves. We have found that power-law log(N(> S))–log(S) curves are a consequence of smooth continuous formation of X-ray binaries and a luminosity break is the signature of a starburst episode in the recent past. The luminosity break is robust and is determined by the lifespans of the X-ray binaries relative to the look-back time to the starburst epoch. The model successfully explains the different forms of log(N(> S))–log(S) curves for the disk and bulge sources in the spiral galaxy M81.

Key words: Missions: Chandra – X-rays: binaries — X-ray: sources in the spiral galaxy M81.

1. Introduction

Recent Chandra observations have shown that nearby spiral galaxies similar to the Milky Way (e.g., M81,\textsuperscript{[Tennant et al. 2004]} contain hundreds of discrete X-ray sources. The source numbers are even large in giant ellipticals, starburst galaxies and mergers (see Sarazin et al. 2000, Matsumoto et al. 2001, Fabbiano et al. 2001). While these sources are an inhomogeneous population, the majority of them are believed to be X-ray binaries (XRBs) containing a black hole or neutron star. The X-rays from these binaries are powered by accretion, with the duration of their X-ray phases limited by the supply of accreting material from their companion stars, which are mostly main-sequence or giant stars. The lifespans of XRBs are therefore finite. If the averaged mass-transfer rates are higher for brighter systems, then brighter XRBs are short-lived.

2. Birth-death model

For the X-ray luminosities of the Chandra sources in galaxies at distances of a few Mpc (L_x > 10^{36} erg s^{-1}), the duration of their mass-transfer (X-ray) phase are shorter than 10^{9} yr. These timescales are short in comparison with the dynamical timescales of galaxies, which are usually longer than 10^{9} yr. XRBs are thus formed and then cease to be X-ray active within the lifetime of their host galaxies. As the formation of XRBs is an ongoing process like the formation of normal stars, XRBs populate not just starburst galaxies but galaxies of different ages and of different Hubble types.

If a galaxy is undisturbed so that its stellar population ages smoothly, then the formation of XRBs is also likely to be a smooth process. If the galaxy has an episode of vigorous star-formation triggered by galactic interaction or merging, then enhancement in the rates of XRB formation will subsequently occur. The XRB populations are therefore tracers of the dynamical history of galaxies.

Here, we construct a birth-death model and use it to describe the time-dependent evolution of the XRB populations in galaxies. We show that the model is able to qualitatively explain the morphology of X-ray luminosity functions of XRBs in nearby galaxies. In particular, the model provides a mechanism for the formation of a luminosity break in the log(N(> S))–log(S) curves of the XRBs (where S is the observed X-ray flux). The implications of the results from this study on our understanding of galactic dynamics and evolution are briefly discussed.
where \( f(L, t) \) is the birth rate and \( g(L, t) \) is the death rate.

### 2.1. An Idealised Case

As a simple illustration, consider the case in which (i) the sources have a finite X-ray phase duration \( t_a(L) \), say, proportional to \( 1/L \), (ii) the source brightnesses are constant throughout the X-ray phase, and (iii) the sources are born at the same time, \( t_a \). We further consider a birth-rate function \( f(L, t) = \lambda(L)\delta(t - t_a) \), where \( \lambda(L) \) is the brightness distribution of the sources at birth, and \( \delta(\cdot) \) is the usual Dirac \( \delta \)-function. In an absolute deterministic case, the death-rate is a time translation of the birth-rate: \( g(L, t) = f(L, t - t_\delta(L)) = \lambda(L)\delta(t - t_a - t_\delta(L)) \).

![Figure 1. The starburst component of the \( N(L) \) curves calculated from the idealised birth-death model (solid lines), without differentiating black-hole and neutron-star binaries. We have assumed that \( t_\delta(L) = (\beta L)^{-1} \), where \( \beta = [0.3 M_\odot c^2]^{-1} \), and that that initial brightness distribution \( \lambda(L) \propto L^{-1.4} \), such that the \( N(L) \) curves have slopes similar to that of the Chandra sources in M81 (see Tennant et al. 2001). Three cases, with \( t(t - t_a) = 0.1, 0.5 \) and 1 Gyr, are shown. Their luminosity cutoffs are at \( 1.7 \times 10^{38}, 3.4 \times 10^{37} \) and \( 1.7 \times 10^{37} \) erg s\(^{-1}\) respectively. The \( N(L) \) curve for the continuous star-formation component is also shown for comparison. We consider only the case in which the slope of \( \tilde{n}_0(L) \) is the same as the slope of \( \lambda(L) \) and the normalisation is \( 1/2 \) of the normalisation of the starburst component.

When \( f(L, t) \) and \( g(L, t) \) are so specified, we can integrate equation (2) with respect to \( t \), yielding

\[
n(L, t) = \tilde{n}_0(L) + (\lambda(L)\theta(t - t_a)[1 - \theta(t - t_a - t_\delta(L))] , (3)\]

where \( \theta(\cdot) \) are the Heaviside unit step-functions. The constant \( \tilde{n}_0(L) \) is zero, because of the assumption that no systems are born except at \( t_a \). The result here is clear — we only see XRB after a time \( t_a \), and we will not see systems with \( L \) after a time \( t_a + t_\delta(L) \). Moreover, the bright systems disappear first, followed by fainter systems.

If \( t_\delta(L) = (\beta L)^{-1} \), where \( \beta \) is a constant, then a step-like luminosity cutoff is formed at \( L_c = (\beta (t - t_a))^{-1} \) in \( n(L, t) \) and in the cumulative luminosity distribution \( N(L) \).

As the XRB population ages, the cutoff migrates from high to low luminosities (Fig. 1).

Galaxies also have continuous formation of XRBs due to ongoing star-formation (such as young high-mass XRBs in the arms of spiral galaxies) or orbital and nuclear evolution of binary systems (such as old low-mass XRBs in elliptical galaxies or in bulges of spiral galaxies). This will produce a population of XRBs in addition to those formed as a result of starbursts. If \( t \) is large such that the birth and death of the XRBs due to continuous formation has reached an equilibrium, such that \( dv(L, t)/dt|_{\text{con}} = 0 \), the linearity of the formulation allows us to simply set a non-zero \( \tilde{n}_0(L) \) in equation (3) and obtain a solution immediately. Provided that the XRB population due to the starburst dominates, the luminosity cutoff should be evident (Fig. 1).

The formulation can be easily generalised to take into account the delay in the XRB formation after a starburst episode at \( t_a \). We can parametrise the delay \( \epsilon(L) \) as a function \( L \), such that \( f(L, t) = \lambda(L)\delta(t - (t_a + \epsilon(L))) \) and \( g(L, t) = \lambda(L)\delta(t - (t_a + \epsilon(L))) \). It is again straightforward to integrate equations (2) and (1) directly and show qualitatively that the shape of the \( N(L) \) distribution of the XRBs obtained in the idealised case still hold. The only difference is that now the luminosity cutoff is no longer step-like. A more realistic and comprehensive modeling of the delay effects will be presented in Wu et al. (in preparation).

### 2.2. A Stochastic Model

The purely deterministic approach given above needs to be modified because the onset of the X-ray phases of XRBs cannot be simultaneous and the systems may undergo transitions between bright and faint states. The observed luminosities \( L \) are not simply the lifespan-averaged luminosities which can be related to the duration of the X-ray active phase. Also, the lifespans of the sources are characterised by their internal clocks, which are the individual source ages \( \tau \), and they are not the same as the external clock by which the time parameter \( t \) specifying the evolution of the XRB population has been defined. The ages of individual systems are not direct observables in the study of populations of XRBs in galaxies. Only globally-averaged properties such as luminosity distributions can be measured. Hence, the death rate, defined in terms of \( t \), cannot be considered as the time translation of the birth rate.

If we assume that the systems with an observed luminosity \( L \) have a death rate which is specified by a probability mortality function \( k(L) \), and that the birth of XRBs is a Poisson process subject to a birth rate at time \( t \), we can construct a simple statistical/stochastic birth-death
As an approximation, we define $k(L)$ to be the inverse of the characteristic lifespan $t_x(L)$, such that $t_x(L) \propto 1/L$ implies $k(L) = \beta L$, where $\beta$ is a constant. For simplicity we neglect the delay in the formation of XRBs with respect to the starburst at time $t_a$ and assume that the birth function due to the starburst takes the form $\lambda(L)\delta(t - t_a)$. Thus, we have $f(L, t) = \lambda_0(L) + a\lambda(L)\delta(t - t_a)$, where $\lambda_0(L)$ is the continuous component of the birth rate of XRBs and $a$ is a parameter specifying the relative strength of the starburst component. As $f(L, t)$ and $t_x(L)$ are now specified, equations (4) and (1) can be solved, yielding $n(L, t)$ and $N(> L, t)$.

An important property of the solutions is that, at any time $t$, the starburst component of $n(L, t)$ has a cutoff at a critical luminosity $L_c = [\beta(t - t_a)]^{-1}$. Here the cutoff is exponential, whereas in the idealized deterministic model considered above it is step-like. The location of the cutoff of the two cases is, however, identical. The cutoff causes an exponential luminosity break in the $N(> L)$ distribution. Including time-delay effects in the formulation will not eliminate the luminosity cutoff but, instead, will cause $N(> L)$ to appear as a broken power law for a power-law form $\lambda(L)$ (Soria, private communication). For the continuous component of $n(L, t)$ there is no cutoff at $L_c = [\beta(t - t_a)]^{-1}$. The corresponding cutoff is at $L_c \sim [\beta t_{gal}]^{-1}$, where $t_{gal}$ is the age of the host galaxy. The luminosity break is therefore robust, and it is a characteristic of aging of a population of XRBs born as a consequence of an episode of star-formation in the recent past.

We must emphasize that the results obtained from the above formulation should be interpreted in a probabilistic and statistical context. The formulation allows the presence of systems with luminosity $L$ brighter than the characteristic cutoff luminosity because the birth of XRBs is a Poisson process in the time domain and because the observed $L$ is an instantaneous quantity while the duration of the X-ray phase of an XRB is related only to the luminosity averaged over the lifespan of the source. Moreover, $n(L, t)$ is the expected value over an ensemble of sources with a distribution of ages which is not directly observable. (For more details, see Wu et al. 2002.)

Nevertheless, the results obtained by the deterministic and stochastic formulations are qualitatively similar, as can be demonstrated using the following example. Consider a simple birth-rate function, $f(L, t) = \lambda(L)[1 + a\delta(t - t_a)]$, where $a$ is now the ratio of the strength of the impulsive starburst component to that of the continuous formation component. (Here we assume the same initial XRB brightness distributions for the two components.) Then we have

$$n(L, t) = n_o(L) e^{-\beta L t} + \lambda(L) \left(1 - e^{-\beta L t}\right) + a\lambda(L)\delta(t - t_a) e^{-\beta L(t - t_a)},$$

where $n_o(L) \equiv n(L, 0)$ is the initial population. By comparing the last term in equation (5) with equation (3) (with $t_x(L) = (\beta L)^{-1}$), we can easily see their similar time-dependent behaviours. Also, for $\beta L t \gg 1$, the second term in equation (5) becomes $\lambda(L)/\beta L$, which is independent of $t$ just as is the term $n_o(L)$ in equation (3).

Consider an initial population and a birth rate in power-law forms with the lower cutoff below the limit of detection $L_\ast$, i.e., $n_o = n_\ast(L/L_\ast)^{-\alpha_1}$ and $\lambda(L) = f_\ast(L/L_\ast)^{-\alpha_2}$, where $\alpha_1$ and $\alpha_2$ are constants. Then the cumulative luminosity distribution is

$$N(> L, t) = n_o L_\ast (\beta L, t)^{\alpha_1-1} \Gamma(1 - \alpha_1, \beta L t) + f_\ast (L/\beta L)^{\alpha_2} \left[\frac{1}{\alpha_2} (\beta L)^{-\alpha_2} - 1 - e^{-\beta L t}\right]$$

$$+ \frac{1}{\alpha_2} \Gamma(1 - \alpha_2, \beta L t) + a f_\ast L_\ast (\beta t_{gal})^{\alpha_2-1} \times \Gamma(1 - \alpha_2, \beta L(t - t_a))\delta(t - t_a),$$

where $\Gamma(\alpha, x)$ is the incomplete gamma function.

Figure 2 shows four examples of $N(> L)$ calculated from this model. The luminosity break is clearly present for the impulsive-starburst component. By adjusting the relative strengths of the continuous and starburst components, we can obtain a form of $N(> L)$ which is a single power law or which has a luminosity break. Note the curve in panel (a) are very similar to what is observed in M81 (Fig. 3).

3. DISCUSSION

Above the completeness limit, the log($N(> S)$)–log($S$) curves of XRBs in individual nearby galaxies can be described as a single or a broken power law. Separating the sources in the bulge and disk of the spiral galaxy M81 reveals that the log($N(> S)$)–log($S$) curves of the XRBs in the two galactic components are different (Tennant et al. 2001). While the log($N(> S)$)–log($S$) curve of the disk sources is a single power law, that of the bulge sources is a broken power law. A power-law form for log($N(> S)$)–log($S$) curve is generally found for XRBs in galaxies or galactic components with strong ongoing star-formation activity (e.g., the disk of M101, Pence et al. 2001 the nuclear region of M83, Soria & Wu 2002 and the starburst galaxy M82). Broken power-law log($N(> S)$)–log($S$) curves are, on the other hand, found for the sources in early-type galaxies (e.g. NGC 4697, Sarazin et al. 2000) and the bulges of spiral galaxies (e.g. M31, Supper et al. 2001). Sarazin et al. (2000) proposed that the luminosity break is caused by a population of XRBs containing a neutron
Figure 2. The $N(> L)$ curves of XRBs in a galaxy calculated from the stochastic birth-death model without differentiating black-hole and neutron-star binaries. The parameters $\lambda_c \equiv (f_{os}/n_{os}L_*)$ and $\lambda_a \equiv (a f_{os}/n_{os})$ specify the contributions of the continuous and the impulsive starburst component respectively. The parameter $\beta$ is set to be [0.3 $M_\odot c^2$]^{-1}, and the power-law indices $\alpha_1$ and $\alpha_2$ are both fixed at 0.4. (a): The starburst epoch occurred 400 million years ago ($t - t_a = 0.4$ Gyr). The values for $\lambda_c$ and $\lambda_a$ are 1.0 and 0.23 respectively. The normalisation is chosen such that the source counts are similar to the number of the M81 bulge sources observed by Chandra (see Tennant et al. 2001). The primordial component is represented by the dashed line; the continuous component by the dot-dashed line; and the impulsive starburst component by the dotted line. The total population is represented by the solid line. (b): Same as (a) except $\lambda_a = 0.03$. (c): Same as (a) except $\lambda_c = 0.1$. (d): Same as (a) except $t - t_a = 1$ Gyr.

While it is possible that the luminosity breaks in the log($N(> S)$)–log($S$) curves of elliptical galaxies are caused by the luminosity limit of neutron-star XRBs, the luminosity breaks in the log($N(> S)$)–log($S$) curves of M31 (Shirey et al. 2001) and of the bulge sources in M81 (Tennant et al. 2001) at about $4 \times 10^{37}$ erg s$^{-1}$ must be due to another mechanism.

From the birth-death model, we can see that a natural explanation for the luminosity break is the aging of a population of XRBs born at approximately the same time in the recent past. If this explanation is correct, then the location of the break marks the starburst epoch and the luminosity function becomes an indicator of the age of the host galaxy (or the host galactic component). The location of the break for the Chandra sources in the M81 bulge, for example, indicates that ($t - t_a \approx 0.4$ Gyr, which is consistent with the time M81 underwent a close encounter with its neighbor M82 (deGrijs et al. 2001).