Models for Low-Mass X-Ray Binaries in Elliptical Galaxies
NGC3379 and NGC4278

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Abstract. We present theoretical models for populations of low-mass X-ray binaries in two elliptical galaxies: NGC3379 and NGC4278. The models are calculated with the recently updated StarTrack code (Belczynski et al. 2007), and are targeted to modeling and understanding the origin of the X-ray luminosity functions (XLF) in these galaxies. For the first time we explore the population XLF down to luminosities of $3 \times 10^{36}$ erg s$^{-1}$, as probed by the most recent observational results (Kim et al. 2006). We consider models for the formation and evolution of low-mass X-ray binaries (LMXB) in galactic fields with different common envelope efficiencies, stellar wind prescriptions and initial mass functions. We identify models that produce an XLF in excellent agreement with the observations both in shape and number of systems at a specific luminosity. We also find that the treatment of the outburst luminosity of transient systems remains a crucial parameter for the determination of the XLF as the modeled populations are dominated by transient X-ray systems.

1. Introduction

An LMXB is a Roche lobe overflowing, mass-transfering binary system with a compact object accretor (acc), which can be either a black hole (BH) or a neutron star (NS), and a low mass ($> 1 M_\odot$) donor (dn). Since the late 80’s it has been suggested that LMXBs should exist in early type galaxies, E and S0, and that they might even dominate the X-ray emission (Trinchieri and Fabbiano 1985). The stellar populations in early type galaxies are typically old and homogeneous. Massive stars have already evolved to compact objects and LMXBs are probably the only sources with X-ray luminosities above $10^{36}$ erg/s.

Recent Chandra observations (Kim et al. 2006) have yielded the first low-luminosity XLFs of LMXBs for two typical old elliptical galaxies, NGC3379 and NGC4278. The detection limit in these observations is $\sim 3 \times 10^{36}$ erg s$^{-1}$ which is about an order of magnitude lower than in most previous surveys of early type galaxies. The observed XLFs of the two ellipticals extend only up to $6 \times 10^{38}$ erg s$^{-1}$ and are well represented by a single power law with a slope (in a differential form) of $1.9 \pm 0.1$. Terlevich and Forbes (2002) estimated the ages and metallicities of 150 elliptical and late type spiral galaxies; for NGC3379 they are reporting an age of 9.3 Gyr and a metallicity of [Fe/H]=0.16, while for NGC4278 the corresponding values are 10.7 Gyr and [Fe/H]=0.14. The two galaxies have very similar optical luminosities and assuming the same mass-to-light ratio, they should also have very similar masses. Colbert et al. (2004) calculated the stellar mass-to-light ratio for the K band, using the B-K color index, for a list of nearby galaxies including NGC3379. The mass of NGC3379 derived in that work was $3 \times 10^{10} M_\odot$. More recently Cappellari et al. (2006) did a similar analysis, using I-band observations from the Hubble Space Telescope and an updated value for their distances, where the masses of the two galaxies were calculated to be $8.6 \times 10^{10} M_\odot$ and $9.4 \times 10^{10} M_\odot$ for N3379 and N4278 respectively.
In this paper we investigate the plausibility of an important contribution to the XLFs of these two galaxies from a primordial galactic field LMXB population using advanced population synthesis simulations.

2. LMXB Population Models

For the models presented in this study we focus on LMXBs formed in the galactic field as products of the evolution of isolated primordial binaries. We perform our simulations with StarTrack (Belczynski et al. 2002, 2007), an advanced population synthesis code that has been tested and calibrated using detailed mass transfer star calculations and observations of binary populations, and incorporates all the important physical processes of binary evolution.

We focus on trying to understand the XLF characteristics of the two elliptical galaxies NGC3379 and NGC4278, observed with Chandra and reported by Kim et al. (2006). In the development of our models we incorporate our current knowledge about the characteristics of the stellar population in these galaxies. There is however, a number of parameters in our models for which we don’t have any direct guidance from observations, e.g. the star formation history of the two galaxies, the initial mass function (IMF) and the distributions of orbital separation and eccentricity for the primordial binary systems. The specific parameters we used to model the ellipticals NGC3379 and NGC4278 are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star Formation</td>
<td>( \delta ) - function at ( t = 0 )</td>
<td></td>
</tr>
<tr>
<td>Population Age</td>
<td></td>
<td>9 - 10 Gyr</td>
</tr>
<tr>
<td>Metallicity</td>
<td>( Z )</td>
<td>0.03</td>
</tr>
<tr>
<td>Total Stellar Mass</td>
<td>( M_* )</td>
<td>( 6 \times 10^{10} M_\odot )</td>
</tr>
<tr>
<td>Binary Fraction</td>
<td>( F_{\text{bin}} )</td>
<td>50%</td>
</tr>
<tr>
<td>IMF Scalo/Kroupa or Salpeter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common Envelope Efficiency</td>
<td>( \alpha_{\text{CE}} )</td>
<td>50% or 100%</td>
</tr>
</tbody>
</table>

2.1. Models for the X-ray Luminosity Function

In our models we keep track of all the binary properties, including the mass-transfer rate, \( \dot{M} \), as a function of time for populations of accreting NSs and BHs. We use the mass-transfer rates to identify the persistent and transient sources in our simulation results. Binaries for which the mass transfer rate is higher than the critical mass transfer rate, \( \dot{M}_{\text{crit}} \), for the thermal disk instability, are considered persistent sources and their X-ray luminosity \( (L_x) \) is calculated directly from the mass transfer rate as

\[
L_x = \eta_{\text{bol}} \epsilon \frac{GM_{\text{acc}} \dot{M}}{R_{\text{acc}}},
\]

where the radius of the accretor \( (R_{\text{acc}}) \) is 10 km for a NS and 3 Schwarzschild radii for a BH, \( \epsilon \) gives a conversion efficiency of gravitational binding energy to radiation associated with accretion, and \( \eta_{\text{bol}} \) is a factor that converts the bolometric luminosity to the X-ray luminosity in the Chandra energy band (0.3 - 8 keV) (see Belczynski et al. 2007, and references therein).
In the context of thermal disk instability model, mass transferring binaries with \( \dot{M} < \dot{M}_{\text{crit}} \) are considered transient sources, meaning that they spend most of their life in a quiescent state \( (T_{\text{quiescent}}) \), at which they are too faint to be detectable, and they occasionally go into an outburst. The fraction of the time that these systems are in outburst \( (T_{\text{outburst}}) \) defines their duty cycle (DC):

\[
\text{DC} \equiv \frac{T_{\text{outburst}}}{T_{\text{outburst}} + T_{\text{quiescent}}}.
\]

(1)

As a first approximation there has been suggested that transient LMXBs emit at their Eddington luminosity \( (L_{\text{Edd}}) \) when they are in outburst. Portegies Zwart et al. (2005) derived an empirical correlation between the outburst luminosity of Milky Way transient LMXBs with BH accretors and their orbital period \( P \):

\[
L_x = \eta_{\text{bol}} \epsilon \times \min \left( 2 \times L_{\text{Edd}}, 2 \times L_{\text{Edd}} \left( \frac{P}{10\text{h}} \right) \right).
\]

(2)

We can generalize this relation to all transient LMXBs in galaxies other than our own, but we note that there has not been any observational work that shows that NS LMXBs follow a similar trend.

A more physical treatment is to assume that in the quiescent state the compact object does not accrete (or accretes an insignificant amount of mass) and matter from the donor is accumulated in the disk. In the outburst state all this matter is accreted onto the compact object again emptying the disk. Taking into account also that the X-ray luminosity probably cannot exceed \( L_{\text{Edd}} \) by more than a factor of 2 (see Taam et al. 1997), we end up with a definition of the outburst luminosity as:

\[
L_x = \eta_{\text{bol}} \epsilon \times \min \left( 2 \times L_{\text{Edd}}, \frac{GM_{\text{acc}} \dot{M}_{\text{dn}}}{R_{\text{acc}}} \times \frac{1}{\text{DC}} \right).
\]

(3)

In the equation above, DC is unknown. Dobrotka et al. (2006) studied non-irradiated accretion disk models for cataclysmic variables that are thought to experience the same thermal disk instability (dwarf novae). They found a correlation between the system’s DC and the mass loss rate of the donor star \( (\dot{M}_{\text{dn}}) \). The exact relation of these two quantities depends on the values of the disk’s viscosity parameters, but the general behavior can be approximated by:

\[
\text{DC} = \left( \frac{\dot{M}_{\text{dn}}}{\dot{M}_{\text{crit}}} \right)^2.
\]

(4)

Plugging eq.(4) into eq.(3) we eliminate the DC dependence and get an expression for the outburst luminosity of a transient system that depends only on quantities which are directly calculated in our population modeling:

\[
L_x = \eta_{\text{bol}} \epsilon \times \min \left( 2 \times L_{\text{Edd}}, \frac{GM_{\text{acc}} \dot{M}_{\text{dn}}^2}{R_{\text{acc}} \dot{M}_{\text{dn}}^2} \right).
\]

(5)

The accretion disk models by Dobrotka et al. (2006) assume accretion onto a compact object with a hard surface and it is not obvious that the same results will apply for accretion onto a BH.
3. Results and Discussion

We examined 36 population synthesis models, exploring tentatively the parameter space. We found that some of our models produce XLFs which are in very good agreement with the observations, based on both the XLF shape and absolute normalization. There is no unique combination of population synthesis parameters and modeling of transient sources (DC and outburst luminosity) that gives an XLF in agreement with the observations. We conclude that formation of LMXBs in the galactic field via evolution of primordial binaries can have a significant contribution to the total population of an elliptical galaxy, especially the ones with low GC specific frequency such as NGC3379 (Fabbiano et al. 2007). Nevertheless, we are able to exclude the majority of our models as inconsistent with the observations. Our results appear to be robust, especially since we do not have to fine-tune our code parameters in order to get a model that resembles the observed population.

As already suggested by Piro and Bildsten (2002), the LMXB population currently present is dominated by transient systems (thermal disk instability) and with reasonable outburst DCs, they tend to dominate the XLF as well. As a consequence, the XLF shape is rather sensitive to the treatment of these transient systems. In Fig. 1 we show that keeping the same population synthesis parameter and changing only the modeling of transient sources leads to completely different XLFs. When we assume the outburst luminosity of all transient LMXBs to be equal to $L_{\text{edd}}$ (model B5) or apply eq.(2) (model B4) - which was empirically derived for Galactic BH LMXBs - to the whole population, we get XLFs inconsistent with the observed ones regarding both their shape and the total number of sources predicted.

The main LMXB sub-populations that contribute to the model XLFs are NS LMXBs with red giant donors and BH LMXBs with main sequence donors, both with mainly transient systems. Of these, the NS LMXBs are the most dominant and primarily determine the XLF shape in the medium and low luminosity range (below $10^{38}$ erg s$^{-1}$), while the BH LMXBs have a significant contribution to the high-end of the XLF. A population of persistent ultra compact LMXBs with white dwarf donors, as predicted by Bildsten and Deloye (2004) for the GCs, is also present in our models but is small enough that its contribution to the XLF is masked by the NS - red giant systems.

The normalization of the modeled XLFs is a less robust characteristic than its shape. We normalize the models so that the number of the primordial binaries we evolve correspond to the known galaxy masses, given the IMF and the binary fraction. There are however, uncertainties of the order of a few in the determination of the mass of the observed galaxies, due to uncertainties in their distance, the bolometric luminosity and the light to mass ratio. The majority of the models presented here produce the observed number of LMXBs (brighter

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Table 2. Exploring the parameter space

<table>
<thead>
<tr>
<th>Model</th>
<th>$\alpha_{CE}$</th>
<th>IMF</th>
<th>$\eta_{\text{inj}}$</th>
<th>$L_{x,\text{NS}}$</th>
<th>$L_{x,\text{BH}}$</th>
<th>DC$_{\text{NS}}$</th>
<th>DC$_{\text{NS}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>0.5</td>
<td>Scalo/Kroupa</td>
<td>1.0</td>
<td>eq.(5)</td>
<td>eq.(2)</td>
<td>eq.(4)</td>
<td>0.5%</td>
</tr>
<tr>
<td>B0</td>
<td>0.5</td>
<td>Scalo/Kroupa</td>
<td>0.25</td>
<td>eq.(5)</td>
<td>eq.(2)</td>
<td>eq.(4)</td>
<td>0.5%</td>
</tr>
<tr>
<td>B1</td>
<td>0.5</td>
<td>Scalo/Kroupa</td>
<td>0.25</td>
<td>eq.(3)</td>
<td>eq.(3)</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>B2</td>
<td>0.5</td>
<td>Scalo/Kroupa</td>
<td>0.25</td>
<td>eq.(3)</td>
<td>eq.(3)</td>
<td>7%</td>
<td>7%</td>
</tr>
<tr>
<td>B3</td>
<td>0.5</td>
<td>Scalo/Kroupa</td>
<td>0.25</td>
<td>eq.(3)</td>
<td>eq.(3)</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td>B4</td>
<td>0.5</td>
<td>Scalo/Kroupa</td>
<td>0.25</td>
<td>$L_{\text{edd}}$</td>
<td>$L_{\text{edd}}$</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>B5</td>
<td>0.5</td>
<td>Scalo/Kroupa</td>
<td>0.25</td>
<td>eq.(2)</td>
<td>eq.(2)</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>C0</td>
<td>0.5</td>
<td>Salpeter</td>
<td>1.0</td>
<td>eq.(5)</td>
<td>eq.(2)</td>
<td>eq.(4)</td>
<td>0.5%</td>
</tr>
<tr>
<td>D0</td>
<td>1.0</td>
<td>Scalo/Kroupa</td>
<td>1.0</td>
<td>eq.(5)</td>
<td>eq.(2)</td>
<td>eq.(4)</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
Figure 1. **Left panel:** Model XLFs for all the different LMXB population models listed in Table 2. In each panel, all the population synthesis parameters are kept constant, and only the modeling of transient systems changes. For comparison the observed XLFs of NGC3379 and NGC4278 are drawn. The modeling of the transient systems and their outburst characteristics can be more important than the usual population synthesis parameters; Commonly used assumptions such as assigning the outburst luminosity of the transient LMXBs to be equal to $L_{\text{edd}}$ (model B4) lead to XLFs clearly inconsistent with the observations. **Right panel:** Analysis of the LMXB population. We show the contribution of different sub-populations by separating the LMXBs into groups of systems with different donor stellar types. Transient systems are drawn with grey color while persistent ones with back. We find that the mid-range of the XLF is dominated by NS LMXB with red giant donors while the high-end by BH LMXBs with main sequence donors.

than the observational sensitivity limit) to within a factor of 3, which is consistent with the galaxy mass uncertainties.

For a more extensive analysis see Fragos et al. (2008)

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**References**

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