THE GALACTIC POPULATION OF LOW- AND INTERMEDIATE-MASS X-RAY BINARIES

ERIC PFHAŁ, SAUL RAPPAPORT, AND PHILIPP PODSIADŁOWSKI

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ABSTRACT

We present the first study that combines binary population synthesis in the Galactic disk and detailed evolutionary calculations of low- and intermediate-mass X-ray binaries (L/IMXBs). This approach allows us to follow completely the formation of L/IMXBs, and their evolution through the X-ray phase, to the point when they become binary millisecond pulsars (BMPs). We show that the formation probability of IMXBs with initial donor masses of 1.5–4 $M_\odot$ is typically $\gtrsim$5 times higher than that of standard LMXBs with initial donor masses of $<1.5M_\odot$. Since IMXBs evolve to resemble observed LMXBs, we suggest that the majority of the observed systems may have descended from IMXBs. Distributions at the current epoch of the orbital periods, donor masses, and mass accretion rates of L/IMXBs have been computed, as have orbital-period distributions of BMPs. Several significant discrepancies between the theoretical and observed distributions are discussed. We find that the total number of luminous ($L_X > 10^{36}$ ergs s$^{-1}$) X-ray sources at the current epoch and the period distribution of BMPs are very sensitive to the parameters in analytic formula describing the common-envelope phase that precedes the formation of the neutron star. The orbital-period distribution of observed BMPs strongly favors cases where the common envelope is more easily ejected. However, this leads to a $\gtrsim 100$-fold overproduction of the theoretical number of luminous X-ray sources relative to the total observed number of LMXBs. X-ray irradiation of the donor star may result in a dramatic reduction in the X-ray active lifetime of L/IMXBs, thus possibly resolving the overproduction problem, as well as the long-standing BMP/LMXB birthrate problem.

Subject headings: binaries: close — pulsars: general — stars: neutron — X-rays: stars

1. INTRODUCTION

Roughly 140 low-mass X-ray binaries (LMXBs) are known in the Galaxy (?), with orbital periods from 11 min to $\sim$1 yr, donor masses of $\sim$0.01–2 $M_\odot$, and X-ray luminosities from the detection sensitivities to $\sim 10^{38}$ ergs s$^{-1}$. Over the past twenty years or so, many theoretical studies of LMXBs have aimed at accounting for their abundance and variety. During this time, a standard picture for the formation and evolution of LMXBs in the Galactic disk has emerged. However, recent observational and theoretical work have challenged the conventional wisdom and prompted a renewed interest in the origins of observed LMXBs. Specifically, it has been realized that many, perhaps even the majority, of the identified LMXBs with low-mass stellar companions may be descendants of systems with intermediate-mass ($\gtrsim 1.5M_\odot$) donor stars.

In the past, all binary population synthesis studies that explicitly considered the evolution of X-ray binaries and the criteria for dynamically unstable mass transfer involved analytic approximations (?), e.g.,) rappaport82b, kalogera96a, king99. This is a satisfactory approach as long as the structure of the donor star and its response to mass loss can be described using relatively simple prescriptions; however, this is not possible in general. The clear and widespread realization that intermediate-mass donor stars can stably transfer matter to a neutron star (NS) accretor came largely as a result of recent calculations that utilized full stellar evolution codes (?), e.g.,) tauris99, podsi00, kalib06, podsi02. Only with such codes can the evolution of the donor be followed realistically during the rapid phase of thermal timescale mass transfer that characterizes the early evolution of intermediate-mass X-ray binaries (IMXBs). ?)[hereafter, Paper I] podsi02 is devoted to a systematic evolutionary study of L/IMXBs, wherein we describe a library of 100 evolutionary sequences computed with a standard Henyey-type stellar structure code. This library has now been expanded to 144 sequences, covering initial orbital periods from 2 hours to 100 days and initial donor masses from 0.3 to $7M_\odot$. The library is intended to provide a fairly complete mapping of the initial conditions that are likely to be encountered in a population synthesis study of L/IMXBs.

Here we extend the work in Paper I by combining our library with a detailed Monte Carlo binary population synthesis (BPS) code for L/IMXBs. The code includes standard assumptions for the population of massive primordial binaries, reasonable analytic prescriptions to describe both stable and dynamically unstable mass transfer prior to the supernova (SN) explosion, and NS kicks. Similar codes are described in ?) and ?).

We undertake a limited exploration of the set of free parameters that enter the BPS calculation used to generate the incipient X-ray binaries. Probably the most important parameters in the BPS study are the mean NS kick speed and the envelope binding energy that enters the prescription for common-envelope evolution. For reasonable variation of these two quantities, the formation probability of L/IMXBs ranges over two orders of magnitude.

For each incipient L/IMXB that emerges from the BPS calculation, we find an initial model in our library with the closest matching orbital period and donor mass. For the ensemble of selected sequences, we apply a temporal weighting scheme to calculate the distributions of potentially observable quantities at the current epoch. This is the first paper where such distribu-
tions have been computed for L/IMXBs, and it is now possible to directly compare population models and the statistics of observed systems.

The paper is organized as follows. In § 2, we briefly describe our BPS code, highlighting the important uncertainties and the associated free parameters. The population of incipient X-ray binaries that emerges from the BPS calculation is discussed in § 3. Key results of this study are presented in § 4, where we show distributions of various quantities at the current epoch and make rough comparisons with the observational data. Finally, in § 5, the most important results of our investigation are listed, along with suggestions for how this work may be extended and improved.

2. MASSIVE POPULATION SYNTHESIS

The formation of a NS in a binary system involves three main evolutionary steps: (1) the formation of a primordial binary, where the initially more massive component (the primary) has a mass \( M_1 \geq 8M_\odot \), (2) a phase of mass transfer from the primary to the secondary (the initially less massive component), and (3) the subsequent SN explosion of the primary’s hydrogen-exhausted core and the formation of the NS. Our Monte Carlo BPS code utilizes a set of analytic prescriptions to describe each of these steps. A brief overview of the important elements of our code is given below; an expanded account is provided in ?).

2.1. Primordial Binaries

We construct each primordial binary by selecting the component masses and orbital parameters from the following distribution functions.

**Primary Mass.** —The initial primary mass, \( M_{1i} \), is chosen from a power-law initial mass function, \( p(M_{1i}) \propto M_{1i}^{-3} \). We use a fixed value of \( x = 2.5 \) for massive stars (?, e.g.,)miller79,scalo86a,kroupa93. Primary masses are restricted to the range \( M_{1i} = 8-25M_\odot \), and we assume that the primary is always the NS progenitor (?, see, however,)pods92,pols94,wellstein01.

**Secondary Mass.** —The initial secondary mass, \( M_{2i} \), is chosen from a distribution in mass ratios, \( p(q_i) \propto q_i^{\gamma} \), where \( q_i = M_{2i}/M_{1i} < 1 \). Strongly motivated by the work of (?), we prefer a flat distribution (\( \gamma = 0 \)), but we also consider \( \gamma = -1 \) and \( \gamma = 1 \).

**Eccentricity.** —Without much loss in generality, we take the primordial binary orbits to be circular. This assumption is discussed in ?).

**Semimajor Axis.** —The initial orbital separation, \( a_i \), is drawn from a distribution that is uniform in \( \log a_i \) (?, e.g.,)abt78. We determine the minimum value of \( a_i \) for each system by demanding that neither star overflows its Roche lobe on the main sequence. The upper limit is somewhat arbitrary, but here is taken to be \( 10^3 \) AU.

2.2. Mass Transfer

If \( a_i \approx 5-10 \) AU, the primary will grow to fill its Roche lobe at some point during its evolution. The subsequent phase of mass transfer is of crucial importance in determining what types of NS binaries are ultimately produced. It is common practice to distinguish among three main evolutionary phases of the primary at the onset of mass transfer (?). Case A evolution corresponds to core hydrogen burning, case B refers to the shell hydrogen-burning phase, but prior to central helium ignition, and case C evolution begins after core helium burning. It is quite improbable for mass transfer to begin during core helium burning, and we thus neglect this possibility (?, see)pfahl02e. We refer to as case D the large fraction of wide binaries that remain detached prior to the SN explosion of the primary. Using the distributions and standard-model parameters given above, as well as the treatment of stellar winds discussed below, we find that cases A, B, C, and D comprise roughly 5%, 30%, 15%, and 50%, respectively, of the primordial binary population. In order to determine which case each binary falls into, we use the single-star evolution fitting formulae of ?.

Mass transfer from the primary to the secondary may be **stable or dynamically unstable**, depending mainly on the binary mass ratio and evolutionary state of the primary when it fills its Roche lobe. In our population study of L/IMXBs, we consider only cases B and C mass transfer. Case A mass transfer accounts for only a small fraction of the binaries and, furthermore, most likely leads to the merger of the two stars following a contact phase (?). Most case D systems are disrupted due to the SN explosion of the primary if NS kicks are significant. We do not consider case D systems that survive the SN; for a discussion of the products that may emerge from this evolutionary channel, see ? and ?.

Cases B and C are divided in early (B, or C_e) and late (B_l or C_l) phases, if the primary has an envelope that is mostly radiative or deeply convective, respectively. We assume that mass transfer is stable, though non-conservative, for cases B, and C_e if the mass ratio, after any wind mass loss has occurred, is \( q_c > 0.5 \), where \( q_c \) is some critical mass ratio. We adopt a fixed value of \( q_c = 0.5 \) in our study (?, e.g.,)wellstein01. If the primary has a deep convective envelope when it fills its Roche lobe, mass transfer is dynamically unstable and a common-envelope (CE) phase ensues, which results in either a very compact binary or a merger.

A single star of mass \( \gtrsim 15M_\odot \) may lose \( \gtrsim 30\% \) of its mass in a stellar wind on the asymptotic giant branch (AGB). For stars of mass \( \lesssim 25M_\odot \), only \( \leq 5\% \) of the mass is lost on the main sequence. We suppose that the wind from the primary in a binary system takes with it the specific orbital angular momentum of the star. If the AGB winds, the Roche lobe of the primary expands and may overtake the expansion of the star, making Roche-lobe overflow and case C_l mass transfer impossible. We have included the effects of stellar winds only for initial primary masses >13M_\odot, on both the main sequence and the AGB; our procedure is similar to the one adopted by ?). For this range of masses, core helium burning begins while the star is in the Hertzprung gap, and there is no decrease in the stellar radius. Primaries of mass \( M_1 \lesssim 13M_\odot \) experience moderate wind mass loss during core helium burning following evolution through the first giant branch, but the stellar radius decreases after helium ignition, precluding Roche-lobe overflow during this phase. We note that the mass that separates the two behaviors just mentioned is actually quite uncertain (?), and may be as large as \( \approx 20M_\odot \).

If a merger is avoided, it is reasonable to suppose that the primary loses its entire envelope, leaving only its hydrogen-exhausted core, irrespective of whether mass transfer is stable or dynamically unstable. Following case B mass transfer, the mass of the helium core is given approximately by (?)

For our chosen maximum primary mass of \( 25M_\odot \), the cor-
responding core mass is $\approx 8M_\odot$. A nascent helium star of mass $3-8M_\odot$ that is exposed following case B mass transfer may lose 10–30\% of its mass in a wind before the SN (\textcolor{black}{\textit{?, e.g.,}})\textit{brown01,pols02}. The final core mass is related to the initial helium star mass by the approximate formula (\textcolor{black}{\textit{?, see Fig. 1 of}})\textit{pols02}

If $M_{ci} \lesssim 3M_\odot$, following case B mass transfer, we may safely neglect winds, but such helium stars may expand to giant dimensions following core helium burning, often initiating a phase of so-called case BB mass transfer to the secondary (???). We do not attempt to model this evolution in detail, but simply assume that $0.5M_\odot$ is transferred conservatively from the primary’s core to the secondary. In case BB systems where $M_{ci} < M_{ci}$, such as when the secondary is of low- or intermediate-mass, the mass transfer may proceed on the thermal timescale of the core, and the evolution may be quite complicated (\textcolor{black}{\textit{?, e.g.,}})\textit{dewi02,ivanova03}. However, any reasonable treatment of case BB mass transfer is not likely to change our results for L/IMXBs substantially.

Stable mass transfer from the primary to the secondary is treated analytically as follows. We assume that the secondary accretes a fraction $\beta$ of the material lost from the primary during Roche-lobe overflow. The complementary mass fraction, $1-\beta$, escapes the system with specific angular momentum $\alpha$, in units of the orbital angular momentum per unit reduced mass. We use constant values of $\alpha = 1.5$, characteristic of mass loss through the L2 point, and $\beta = 0.75$. The final orbital separation is then given by the generic equation (\textcolor{black}{\textit{?}})

It is easily verified that, in our simulations, the minimum secondary mass resulting from stable mass transfer is roughly $q_c 8M_\odot + \beta 6M_\odot$, where $8M_\odot$ is the minimum primary mass and $6M_\odot$ is the corresponding envelope mass shed during mass transfer. For our chosen values of $q_c = 0.5$ and $\beta = 0.75$, this minimum mass is $8.5M_\odot$, considerably larger than the maximum initial donor mass of $\sim 4M_\odot$ for which an IMXB undergoes stable mass transfer (see Paper I). Thus, in our work, all incipient L/IMXBs are the products of dynamically unstable mass transfer.

We use the conventional energy relation to describe the dynamical spiral-in during a CE phase (\textcolor{black}{\textit{?, e.g.,}})\textit{webbink84}. The ratio of the final to the initial orbital separation is given by the generic equation

A sufficient condition for the merger of the primary and secondary is that the main-sequence secondary overfills its Roche lobe for the calculated post-CE orbital separation. Therefore, the minimum separation for surviving systems must be larger than several solar radii, corresponding to initial orbital separations greater than several hundred solar radii. It turns out that the majority of the dynamically unstable case B\textsubscript{e} and C\textsubscript{e} systems merge following the CE, and that in most systems that survive the CE, the primary is a convective red supergiant (case B\textsubscript{f} or C\textsubscript{f}) at the onset of mass transfer.

2.3. Supernova Explosion

After the exposed core of the primary consumes its remaining nuclear fuel, it explodes as a Type Ib or Ic SN and leaves a NS remnant. We take the initial NS mass to be $1.4M_\odot$. Impulsive mass loss and the NS kick strongly perturb the binary and may cause its disruption. Mass loss is especially significant, since the mass ejected may be comparable to or greater than the secondary mass. Some important insights can be obtained rather simply by neglecting NS kicks.

It is straightforward to show (\textcolor{black}{\textit{?, e.g.,}})\textit{blaauw61,boersma61} that for a circular pre-SN orbit and \textit{vanishing kicks} the eccentricity, $e_{SN}$, after the SN is simply

When NS kicks are considered in addition to SN mass, a larger fraction of systems are disrupted, and those binaries that do remain bound will have larger CM speeds. We utilize a Maxwellian distribution in kick speeds.

Significant SN mass loss and large NS kicks yield bound post-SN binaries with high eccentricities. Given the post-SN eccentricity, we check if the radius of the secondary is $>10\%$ larger than its tidal radius at periastron. If this occurs, we assume that the NS immediately spirals into the envelope of the unevolved secondary and do not consider the system further. Our 10\% overflow restriction allows for the possibility that tidal circularization and perhaps some mass loss will prevent the objects from merging. The details of eccentric binary evolution with mass transfer is well beyond the scope of this investigation. However, we note in passing that Cir X-1 is most likely a young, possibly intermediate-mass, X-ray binary undergoing episodic mass transfer as a result of having a highly eccentric ($e_{SN} \gtrsim 0.8$) orbit (\textcolor{black}{\textit{?}}).

If the coalescence of the NS and secondary is avoided, we neglect mass loss from the system and assume, rather simplistically, that the binary circularizes while conserving orbital angular momentum. The final orbital separation is then $d_{SN} (1 - e_{SN}^2)$, where $d_{SN}$ is the semimajor axis after the SN. Moreover, we assume that the secondary rotates synchronously with the circularized orbit.

3. Incipient X-ray Binaries

The output of the population synthesis calculation is a set of circular binaries, each identified by their orbital period and the mass of the secondary. In order to select initial models from our library of L/IMXB evolutionary sequences, we require the orbital period at which the secondary first fills its Roche lobe. Hereafter, we denote the donor and accretor (NS) masses in units of $M_\odot$ by $M_d$ and $M_s$, respectively.

Orbital angular momentum losses via gravitational radiation (GR) and magnetic braking (MB) may cause the binary separation to decrease substantially prior to mass transfer. The timescale for orbital shrinkage due to GR is

The single-star evolution code of (\textcolor{black}{\textit{?)}}) is used to follow the radial evolution of the secondary as MB and GR shrink the orbit. The metallicity is set to the solar value of $Z = 0.02$. We neglect the evolutionary time prior to the SN of the primary and assume that the secondary is on the ZAMS at the time the NS is formed. The age of the secondary when it fills its Roche lobe is here referred to as the “lag time,” denoted by $\tau_{lag}$. The lag time thus approximates the time between the formation of the primordial binary and the onset of the X-ray binary phase. We take the age of the Galaxy to be 13 Gyr, and only accept as incipient L/IMXBs those for which $\tau_{lag} < 13$ Gyr.