BINARITY POPULATION SYNTHESIS: LOW- AND INTERMEDIATE-MASS X-RAY BINARIES

Ph. Podsiadlowski
Oxford University
OX1 3RH, U. K.
podsi@astro.ox.ac.uk

S. Rappaport, E. Pfahl
Department of Physics,
Massachusetts Institute of Technology,
Cambridge, MA 02139
sar@mit.edu, pfahl@mit.edu

Abstract As has only recently been recognized, X-ray binaries with intermediate-mass secondaries are much more important than previously believed. To assess the relative importance of low- and intermediate-mass X-ray binaries (LMXBs and IMXBs), we have initiated a systematic study of these systems consisting of two parts: an exploration of the evolution of LMXBs and IMXBs for a wide range of initial masses and orbital periods using detailed binary stellar evolution calculations, and an integration of these results into a Monte-Carlo binary population synthesis code. Here we present some of the main results of our binary calculations and some preliminary results of the population synthesis study for a “standard” reference model. While the inclusion of IMXBs improves the agreement with the observed properties of “LMXBs”, several significant discrepancies remain, which suggests that additional physical processes need to be included in the model.¹

Keywords: X-ray binaries, millisecond pulsars, binary population synthesis, Cygnus X-2

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1. INTRODUCTION

Until recently it was generally believed that X-ray binaries fall into two distinct classes, low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs), with Her X-1 being the only exception that does not really belong to either class (for a general review see, e.g., Bhattacharya & van den Heuvel 1991). However, in the systems classified as “LMXBs” the nature of the secondary is usually unknown. Whenever it has been possible in recent years to determine the nature of the secondaries in so-called “LMXBs”, these did not actually comply with the standard paradigm for LMXBs. First, van Kerkwijk et al. (1992) showed that the X-ray binary Cyg X-3, until then generally considered a “proto-type LMXB”, actually contained a Wolf-Rayet star and hence, if anything, should be classified as a HMXB. More recently, it was recognized that the second-brightest X-ray source in the same constellation, Cyg X-2, also does not belong to the group of LMXBs, but is the descendant of an intermediate-mass X-ray binary (IMXB; see Sect. 2.1). This latter discovery immediately raises the question whether many other, perhaps even most systems classified as “LMXBs” are in actual fact “IMXBs”.

In order to determine the relative importance of LMXBs and IMXBs we have initiated a systematic binary population synthesis study (Pfahl, Rappaport & Podsiadlowski 2001; Podsiadlowski, Rappaport & Pfahl 2001). Our approach is different from most previous studies in so far as we use realistic binary evolution calculations instead of simplified analytical prescriptions to model individual binary sequences.

In Section 2 of this contribution we first discuss the developments that have led to the re-assessment of the importance of IMXBs; in Section 3 we describe our comprehensive set of binary calculations highlighting some of the main results of these calculations, and in Section 4 we show how we are implementing these sequences into a binary population synthesis code and illustrate this with some preliminary results. For a discussion of the related problem, the formation of X-ray binaries and millisecond pulsars in globular clusters, we refer to the contribution by Rasio (Rasio 2001).

2. THE IMPORTANCE OF INTERMEDIATE-MASS X-RAY BINARIES (IMXBs)

Until recently IMXBs had received relatively little attention (see, however, Pylyser & Savonije 1988, 1989 and in the context of black-hole transients Kolb 1998; Regös et al. 1998). One of the main reasons for this neglect is the fact that only one such system, Her X-1, had unambiguously been identified in the past. This changed recently with two
new developments. First, Davies & Hansen (1998) studying dynamical interactions in globular clusters found that IMXBs are much easier to form dynamically than LMXBs and speculated that these IMXBs, which do not exist in globular clusters at the present epoch, might be the progenitors of the observed millisecond pulsars rather than the presently observed LMXBs.

The second development, which spurred our own investigation, was a re-assessment of the evolutionary status of the X-ray binary Cyg X-2.

2.1. THE CASE OF CYGNUS X-2

The spectroscopic observations of Cyg X-2 by Casares, Charles & Kuulkers (1998) combined with the modelling of the ellipsoidal light
curve (Orosz & Kuulkers 1999) showed that the secondary in Cyg X-2 was indeed a low-mass star with $M_2 = 0.6 \pm 0.13 M_\odot$. However, the same observations also showed that the spectral type of the companion is, to within two subclasses, A9III and that the spectral type does not vary with orbital phase. Since this almost certainly constitutes the intrinsic spectral type of the secondary, it means that the secondary is far too hot and almost a factor of 10 too luminous to be consistent with a low-mass subgiant with an orbital period of 9.84 days (see Podsiadlowski & Rappaport 2000).

A resolution of this paradox was found independently by King & Ritter (1999) and Podsiadlowski & Rappaport (2000) (also see Kolb et al. 2000; Tauris, van den Heuvel, & Savonije 2000) who showed that the characteristics of Cyg X-2 can be best understood if the system was the descendant of an IMXB where the secondary initially had a mass of $\simeq 3.5 M_\odot$ and lost most of its mass in very non-conservative case AB or case B mass transfer. This is illustrated in Figures 1 and 2 (from Podsiadlowski & Rappaport 2000).

Thus, Cyg X-2 provides observational proof that IMXBs can eject most of the mass that is being transferred from the secondary (perhaps in a way similar to what happens in SS433) and subsequently resemble classical LMXBs. This raises the immediate question of what fraction of so-called “LMXBs” are in reality IMXBs or their descendants. It is also worth noting that IMXBs are much easier to form than LMXBs since they do not require the same amount of fine-tuning as LMXBs (see Bhattacharya & van den Heuvel 1991). Furthermore, if there is a large fraction of IMXBs this will not only affect the period and the luminosity distribution of “LMXBs”, but also has important implications for the so-called “LMXB” – ms pulsar birthrate problem (e.g., Kulkarni & Narayan 1988), all issues that can only be properly addressed with the help of binary population synthesis.

3. Binary Sequences for LMXBs and IMXBs

In order to systematically investigate LMXBs and IMXBs, we performed a series of $\sim$100 binary evolution calculations, covering the mass range of 0.8 to 7 $M_\odot$ and all evolutionary phases from early case A to late case B mass transfer.

3.1. Model Assumptions

All calculations were carried out with an up-to-date, standard Henyey-type stellar evolution code (Kippenhahn, Weigert, & Hofmeister 1967),
Figure 2. Key binary parameters for the case AB binary calculation as a function of time (with arbitrary offset). Panel (a): radius (solid curve) and Roche-lobe radius (dot-dashed curve) of the secondary; panel (b): the orbital period (solid curve); panel (c): the mass of the secondary (solid curve) and the primary (dot-dashed curve); panel (d): the mass-loss rate from the secondary (solid curve); the inset shows a blow-up of the second slow mass-transfer phase (hydrogen shell burning). The dashed curves in panel (b) and (d) show the orbital period and mass-transfer rate for the case B calculation for comparison (from Podsiadlowski & Rappaport 2000).

which uses OPAL opacities (Rogers & Iglesias 1992) complemented with those from Alexander & Ferguson (1994). We use solar metallicity ($Z = 0.02$), a mixing-length parameter $\alpha = 2$ and assume 0.25 pressure scale heights of convective overshooting from the core (Schröder, Pols, & Eggleton 1997). The mass-transfer rate, $\dot{M}$ is calculated explicitly using the formalism of Ritter (1988). We further assume that half the mass transferred is accreted by the neutron star up to the Eddington limit, taken to be $2 \times 10^{-8} M_\odot \text{yr}^{-1}$. Any matter leaving the
Figure 3. Binary evolution tracks in the log $M_2$ – log $P_{\text{orb}}$ plane. The degree of shading measures the amount of time spent in a particular part of the diagram.

Figure 3 presents the evolutionary tracks of our binary sequences in the secondary-mass orbital-period (log $M_2$ – log $P_{\text{orb}}$) plane. Broadly the sequences can be divided into three classes: (1) and (2) systems evolving to long periods and short periods, respectively, separated by the well-known bifurcation period of just under 1 day, and (3) more massive systems experiencing dynamical mass transfer and spiral-in (more easily discerned in Fig. 4). What this figure does not show, however, is the actual variety in these sequences. Some 70 of the $\sim$100 sequences are qualitatively different with respect to the importance and the order of different mass-transfer driving mechanisms, the occurrence of detached phases, the final end products, etc. In this context it is worth noting that there are very few sequences that resemble the classical cataclysmic-variable (CV) evolution where mass transfer is solely driven by gravi-
tional radiation and magnetic braking. This may be important in explaining some of the fundamental differences observed between CVs and LMXBs/IMXBs.

3.2.1 Delayed dynamical instability. The majority of systems in which the initial secondary mass is $4 M_\odot$ and all systems more massive than $4.5 M_\odot$ experience dynamical mass transfer, resulting in the spiral-in of the neutron star inside the secondary. The final outcome of this channel is very uncertain at present, but it may be a spun-up neutron star or a black hole, single or in a very compact binary. In all systems, where the secondary is still on the main sequence when mass transfer starts, this dynamical instability is delayed (see Hjellming & Webbink 1987) since the secondaries initially have radiative envelopes which are stable against dynamical mass loss. Dynamical instability occurs once the radiative part of the envelope with a rising entropy profile has been lost and the core with a relatively flat entropy profile starts to determine the reaction of the star to mass loss. This delay may last for up to $10^6$ yr; during this time the system should still be detectable as a X-ray binary, with a very high mass-transfer rate and quite possibly some unusual properties (such as SS433?) in the last $10^4 – 10^5$ yr before the onset of the dynamical instability.

3.2.2 Evolutionary end products. In Figure 4 we show the final position of the majority of the sequences calculated in the $M_2 – \log P_{\text{orb}}$ plane, where the size of the symbols indicates how much mass the neutron stars have accreted (systems with large symbols may be reasonably expected to contain millisecond pulsars). Circles indicate that the secondary ends its evolution as a He white dwarf. Note that all systems with $P_{\text{orb}} > 0.1$ d lie very close to the relation between white-dwarf mass and orbital period for wide binary radio pulsars calculated by Rappaport et al. 1995 (solid and dashed curves). In systems with triangle symbols, the secondaries burn helium in the core in a hot OB subdwarf phase (after mass transfer has been completed) and become HeCO white dwarfs (i.e., non-standard white dwarfs with a CO core and a large He envelope). Note that these HeCO white dwarfs can have a mass as low as $0.3 M_\odot$, the minimum mass for helium ignition in non-degenerate cores (see, e.g., Kippenhahn & Weigert 1990). Most of these systems lie well below the white-dwarf – orbital period relation without having experienced a common-envelope phase (also see Podsiadlowski & Rappaport 2000; Tauris et al. 2000). It is not immediately clear whether the fact that many of these relatively low-mass white dwarfs have CO cores has detectable, observational consequences.
Finally, it is worth noting that most of the white dwarfs with masses < 0.6 $M_\odot$ experience several dramatic hydrogen shell flashes (typically 2 to 4) before settling on the white-dwarf cooling sequence (these are reminiscent of the final helium shell flashes for relatively massive post-AGB stars; Iben et al. 1983). During these flashes, the luminosity typically rises by a factor of 1000 and the radius increases by a factor of 10 or more on timescales of a few decades. Indeed, during these flashes the secondaries tend to fill their Roche lobes again, leading to several short mass-transfer phases with very high mass-transfer rates driven entirely by the dynamics of these flashes.
3.3. THE FORMATION OF ULTRA-COMPACT BINARIES

As Figures 3 and 4 show, systems with initial orbital periods somewhat less than $\sim 1\, \text{d}$ lead to ultra-compact binaries with minimum orbital periods in the range of $20 - 90\, \text{min}$. The shortest period is not much longer than the $11\, \text{min}$ period in the X-ray binary 4U 1820-30 in the globular cluster NGC 6624 (Stella et al. 1987). Unlike the two pop-
ular models for the formation of this system, this evolutionary channel involves neither a direct collision (Verbunt 1987) nor a common-envelope phase (Bailyn & Grindlay 1987; Rasio, Pfahl, & Rappaport 2000) and therefore constitutes an attractive alternative scenario for 4U 1820-30 (this model was first suggested by Tutukov et al. 1987 and was examined in some detail by Fedorova & Ergma 1989).

To determine the shortest orbital period that can be attained through this channel we performed a separate series of binary calculations for a $1M_\odot$ secondary (as would be appropriate for the initial mass of the secondary in 4U 1820-30). We found, confirming the earlier results of Fedorova & Ergma (1987), that, if the secondaries start mass transfer near the end of core hydrogen burning (or, in fact, just beyond), the secondaries transform themselves into degenerate helium stars and that orbital periods as short as 5 min can be attained without the spiral-in of the neutron star inside a common envelope.

The results of this exploration are summarized in Figure 5. As the top panel shows, there is a fairly large range of initial orbital periods (13 – 18 hr) which leads to ultra-compact LMXBs with a minimum orbital period less than 30 min. Indeed, it is remarkable that one of our binary sequences, with an initial orbital period around 17 hr, appears to be a suitable sequence to explain all five LMXBs in globular clusters whose orbital periods are presently known, from the system with the longest period (AC211/X2127+119 in M15; $P_{\text{orb}} = 17.1$ hr; Ilovaisky et al. 1993) to the 11-min binary. Furthermore, systems with an initial period in the range of 13 – 18 hr are quite naturally produced as a result of the tidal capture of a neutron star by a main-sequence star (Fabian, Pringle, & Rees 1975) and are not the generally expected outcome of a 3- or 4-body exchange interaction (see, e.g., Rasio et al. 2000; Rasio 2001). This suggests to us that it may be premature to rule out tidal capture as a formation scenario for LMXBs in globular clusters as has often been done in recent years.

4. BINARY POPULATION SYNTHESIS

For our population synthesis study, we determine, starting from primordial binaries, the mass of the secondary and the orbital period at the beginning of the X-ray binary phase. We then choose the binary sequence from our two-dimensional grid that is closest to this point in the $(M_2, P_{\text{orb}})$ plane to represent the X-ray binary phase. As our systematic exploration of LMXB/IMXB evolution has shown, there is such a large variety of possible binary sequences that one cannot hope that all of them can be well represented by simple (semi-)analytic prescrip-
4.1. MODEL ASSUMPTIONS

For our standard reference model, we pick an initial orbital period distribution that is logarithmically flat, adopt a Miller-Scalo initial mass function for the primary (Miller & Scalo 1979) and a flat distribution for the mass-ratio distribution. For the supernova-kick distribution we choose the Maxwellian distribution with $\sigma = 190 \text{ km s}^{-1}$ from Hansen & Phinney (1997). We plan to investigate the effects of varying these
assumptions as part of our study in the future. To determine the orbital parameters for post-common-envelope systems, we use binding energies for the common envelope obtained from realistic stellar calculations with or without the inclusion of the ionization energy (Han et al. 1995; Dewi & Tauris 2000).

4.2. PRELIMINARY RESULTS

In Figures 6 and 7 we present some of the early results of our population synthesis simulations for our standard set of assumptions. Figure 6 displays the distributions of the secondary mass, orbital period and system space velocity at the beginning of the X-ray binary phase. The mass
distribution is dominated by intermediate-mass systems; the more massive systems (above $\sim 4 M_\odot$) will experience (delayed) dynamical mass transfer and will not contribute significantly to the population of X-ray active systems. At the other end of the mass spectrum, we find very few low-mass, CV-like systems.

Figure 7 in contrast shows the distributions of the secondary mass, orbital period and neutron-star mass-accretion rate during the X-ray binary phase at the current epoch. Now the mass distribution is dominated by relatively low-mass systems, and there are hardly any systems above $\sim 2 M_\odot$. The reason is simply that the intermediate-mass systems lose most of their mass rapidly in the initial super-Eddington phase and spend most of their lives at relatively low masses (see Figs 2 and 3). The orbital-period distribution shows no period gap and extends to very low periods. Finally, the luminosity distribution displays a fairly strong peak around $5 \times 10^{-11} M_\odot \text{yr}^{-1}$ and has a sharp cut-off at $\sim 10^{-11} M_\odot \text{yr}^{-1}$.

While these distributions show many of the characteristics of the observed distributions of “LMXBs”, in fact more so than a model that only includes CV-like systems, there are still some fairly obvious discrepancies. First, there are too many short-period systems to be consistent with the observed period distribution (e.g., Ritter & Kolb 1998), although we note that, in this preliminary calculation, we did not consider whether systems are transients or not. Second, while the distribution of mass-accretion rate (and hence X-ray luminosity) has a sharp cut-off at $\sim 10^{-11} M_\odot \text{yr}^{-1}$ — as is desirable, the peak in the distribution is probably too low by about an order of magnitude.

5. OUTLOOK

The binary-population synthesis results presented in this contribution represent only a first step in our investigation. By defining a standard reference model, we can quantitatively identify the problems with this model (e.g., concerning the period and luminosity distributions of LMXBs/IMXBs, the properties of binary millisecond pulsars, etc.). Having identified the problems, we can then examine possible solutions. Some of the modifications we plan to consider are cyclical mass transfer due to external irradiation, interrupted mass transfer and the role of the pulsar turn-on. To first order, we intend to implement these using a perturbation-style approach where we use the available grid of binary sequences to define the secular evolution.

Once we have developed a better model, we can then extend the present calculations with the improved model on a much finer grid. With the improvements in computing power and implementing a ‘minimalistic’
version of our binary stellar-evolution code, we estimate that even with present-day workstations we should be able to calculate one whole binary sequence in about 2 minutes. An attractive alternative is to use the ‘Eggleton’ supercluster at the Lawrence Livermore Laboratory whose potential was impressively demonstrated at this meeting (Eggleton 2001). The ultimate goal, of course, is to obtain a realistic modelling of the X-ray binary population, a goal that now appears achievable within the next few years.

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