The evolution of low–mass X–ray binaries

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Abstract. This brief review addresses our current understanding (or lack thereof) of the long-term evolution of low-mass X-ray binaries. Similarities and differences between the evolution of low-mass X-ray binaries and cataclysmic variables will be emphasized. Particular attention is paid to the following points: a) the evolutionary history and the evolutionary state of the donor star, b) systemic loss of orbital angular momentum, c) other modes of mass and angular momentum loss from the binary system, d) the possible role of irradiation of either the donor star or the accretion disc by accretion luminosity from the vicinity of the compact star, and e) low-mass X-ray binaries as progenitors of binary millisecond pulsars.

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INTRODUCTION

In the context of this brief review, low-mass X-ray binaries (LMXBs) are semi-detached binaries in which either a neutron star (NS) or a stellar mass black hole (BH) primary accretes from a low-mass secondary ($M_2 \lesssim 1.5 M_\odot$). In cases where the primary is a BH stable mass transfer is also possible if the donor star is of intermediate mass with $M_2 \lesssim M_{\rm BH}$. Such systems are usually referred to as intermediate mass X-ray binaries (IMXBs). This article mainly addresses aspects of the evolution of individual systems whereas collective properties and population synthesis of LMXBs and IMXBs are addressed in [1].

The principles of the long-term (secular) evolution of semi-detached binaries have been outlined in detail in [2], and will not be repeated here for reasons of space limitation. Based on time scale arguments it is obvious that mass transfer in the vast majority (if not all) of the observed LMXBs and IMXBs is thermally and adiabatically stable. Therefore, Eqs. (1.8) and (1.12) in [2] apply for describing the secular evolution of these systems. Although these equations are of little practical use for actually computing the mass transfer rate in a semi-detached binary, they illustrate clearly which properties of a binary system have to be known to be actually able to compute the mass transfer rate and thus the secular evolution numerically. First the precise evolutionary state of the donor, i.e. its mass, chemical composition and thermal structure, and thus the full evolutionary history before the onset of mass transfer need to be known. Second, the rate of systemic loss of orbital angular momentum and thus the mechanisms of angular momentum loss at work must also be known. Third, one has to model (or specify) the loss of mass from the binary and the orbital angular momentum which is carried away with it. In the next two sections these aspects are addressed separately and in more detail.

The structural similarity of LMXBs to catalysmic variables (CVs), where in the latter the compact accretor is a white dwarf (WD) rather than a NS or a BH, suggests that also the long-term evolution of LMXBs is similar to that of CVs. However, there are also a number of important differences between LMXBs and CVs which can lead to quite different evolutionary behaviour. This will be discussed in more detail in the penultimate section. Finally, it is widely accepted that LMXBs are progenitors of binary millisecond pulsars (msPSRs). Therefore, in the final section we examine what can be learned about the evolution and population of LMXBs from comparing the properties of known LMXBs with those of binary msPSRs.

THE DONOR STARS OF LMXBS

Observations

Observationally very little is known about the evolutionary state of the donor stars in LMXBs. In the majority of cases not even the donor's spectral type is known. The main reason for this is that during the X-ray active phases of an LMXB the light of the relatively faint secondary is swamped by accretion luminosity, and therefore remains undetectable. Spectral information about the donor and with it stellar parameters become available only if either the system is transient, in which case the secondary can be seen during quiescence, or if the donor itself is relatively luminous, i.e. if it is either an intermediate mass star as in the IMXBs V1033 Sco (GRO J1655–40), IL Lup (4U 1543–37) or V4641 Sgr (SAX J1819.3–2525), or a giant as in V404 Cyg (GS 2023+338), V395 Car (2S 0921–63) or V1487 Aql (GRS 1915+105) (for a compilation of binary and stellar parameters of LMXBs and IMXBs as well as the relevant references see [3]). Because the property of being a transient X-ray binary is strongly correlated with a combination of long orbital period ($P \gtrsim$ few days) and large mass ratio M_1/M_2 (see [4]) it is not surprising that most of the known donor stars are found in BH-LMXBs and show signs of advanced nuclear evolution. Cases in point are V1487 Aql, V395 Car, and V404 Cyg, where the donor is obviously a low-mass giant, and V1033 Sco and V4641 Sgr where the donor is either already in the Hertzsprung gap or near the terminal age main sequence. In addition, there are the ultra-short period LMXBs with orbital periods 11 min $\lesssim P_{\rm orb} \lesssim$ 60 min [3], where the donor is a very low-mass degenerate dwarf. Finally there are also systems like V1341 Cyg (Cyg X-2) where the donor is a low-mass He-star in a phase of very late Case B mass transfer to its NS primary [5, 6].

Theoretical considerations

Stellar evolution, single or binary, is an initial value problem. As has been pointed out in the introduction, computing the secular evolution of a LMXB requires knowledge of the complete evolutionary history of the donor star up to the onset of the mass transfer phase one wishes to model. Whereas the evolution of single stars is comparatively well understood, binary evolution is not. The main reason for this is that from the beginning of its evolution (both components on the zero age main sequence) a binary system is subject to loss of mass and angular momentum from the system via various mechanisms (e.g. common envelope evolution [7, 8], ejection of mass via the Jeans mode, see e.g.

[5], mass loss via stellar winds, systemic angular momentum loss, e.g. via magnetic braking [9, 10, 11], and, last but not least, explosive mass loss in the supernova explosion with which the compact component is formed and the associated supernova kicks), all of which are not sufficiently well understood to allow for a parameter-free description of the resulting mass and angular momentum loss. Thus the evolutionary state of the donor star at the onset of the X-ray phase and the subsequent evolution of a LMXB, depend both on numerous more or less free parameters. As a result, an unambiguous forward integration in time of the evolution of a binary star to the LMXB state is not possible at present. It is in this context that binary population synthesis techniques (for a review see [1]), by comparing theoretical predictions with the observed properties of a whole population, can help constrain some of the free parameters or isolate the crucial mechanisms involved in the formation of LMXBs.

MASS AND ANGULAR MOMENTUM LOSS PROCESSES

In the following the main mass and angular momentum loss processes which are potentially important for the formation and the evolution of LMXBs are briefly discussed.

Mass loss via stellar winds

The progenitors of BHs (and some NSs) start their evolution as very massive stars on the main sequence. A massive star loses a substantial fraction of its initial mass already during its main sequence evolution via a strong stellar wind. Later during its evolution towards the compact component of a LMXB the massive primary loses its remaining hydrogen-rich envelope in a common envelope phase (discussed below). The resulting He-burning core is itself a very luminous (Wolf-Rayet) star which loses mass via a stellar wind at a high rate until core collapse ends this phase. Whereas the wind mass loss rates of massive stars on or near the main sequence can now be modelled with some accuracy [12], the same is hitherto not true for the post common-envelope He-stars. Depending on the rather uncertain mass loss rates of He-stars, the remnant core mass at the time of the supernova explosion does not or does allow for the formation of a massive stellar mass BH (with a mass of $10M_\odot \lesssim M_{\rm BH} \lesssim 15M_\odot$, see e.g. [13]). When computing the angular momentum loss which goes with the wind mass loss it is usually *assumed* that the matter carries away the specific orbital angular momentum of the source (so-called Jeans mode). Thereby the interaction of the stellar wind with the companion's orbital motion with respect to the wind, i.e. the possible transfer of orbital angular momentum of the companion to the wind (see e.g. [14] for the same effect in a different context) is neglected.

Consequential angular momentum loss (CAML)

CAML is loss of orbital angular momentum as a direct consequence of mass transfer in a binary system. CAML is one of the most troublesome aspects of binary evolution to deal with because its computation is tantamount to modelling the (magneto-) hydrodynamical interaction of the outflowing gas with the binary's orbital motion and to modelling the mass loss process itself. This is not what is done in usual binary evolution models. Rather CAML is described by two (almost) free parameters, one specifying the fraction of the transferred mass that is lost from the system, the other the specific angular momentum carried away. Only in exceptional cases can one argue for simple approximations such as CAML in the Jeans mode. A case in point is the ejection of transferred matter from the compact star via jets which do not interact strongly with the components' orbital motion. A possible example for such a situation is discussed in [5].

Common envelope (CE) evolution

CE evolution is probably the single most important process involved in the formation of very close compact binaries [7, 8]. Because to this date it has not been possible to compute the evolution of a binary through the CE phase self-consistently from the onset of mass transfer to the end of envelope ejection, this process is usually dealt with in a parametrized form [7]. Two parameters enter the problem in the simplest approximation, one an efficiency parameter (usually denoted as $\alpha_{\rm CE}$) and a parameter λ which is a measure for the binding energy of the envelope to be unbound by the CE process. Because $\alpha_{\rm CE}$ and λ appear only as a product $\alpha_{\rm CE}\lambda$, CE is essentially parametrized by this one quantity. Recent attempts to compute λ (e.g. [15, 16, 17]) which have yielded ambiguous results because of the freedom in the choice of the core-envelope boundary, do not help much as long as we do not also have a better idea of how large $\alpha_{\rm CE}$ is. Therefore the treatment of CE evolution, i.e. the choice of $\alpha_{\rm CE}\lambda$, is the biggest uncertainty in modelling the formation of compact binaries (see also [1]).

Systemic loss of orbital angular momentum

This mode of angular momentum loss which operates also in the absence of mass transfer is not only important for driving mass transfer in semi-detached compact binaries but also for contracting detached post CE binaries to the onset of mass transfer. In this context two mechanisms need to be mentioned:

a) Gravitational radiation [18]
   This is the only systemic angular momentum loss mechanism for which the rate of angular momentum loss is computable from first principles.
b) Magnetic braking (MB)
   This process, which has been invoked for more than 20 years in the evolution of close binaries [19, 20] using various semi-empirical prescriptions [9, 10], has recently come under attack: the authors of [11] argue that MB in close binaries is much less efficient than according to [9, 10]. Yet estimates of the surface temperatures of accreting WDs in CVs [21] suggest that the mass transfer rates in long-period CVs ($P \gtrsim 3^{\rm h}$) is more in line with what [9, 10] yield rather than with predictions of [11]. Nevertheless, there is currently much uncertainty about the efficiency

of MB in close binaries. And even if [9, 10] yield the correct order of magnitude of braking, one has to keep in mind that the braking rates derived by [9, 10] are semi-empirical estimates, not calculations from first principles, and contain at least one or even several free parameter(s), the value(s) of which is (are) not precisely known.

Supernova explosions and supernova kicks

The mass loss associated with a supernova explosion, if it occurs in a binary system, either makes the post-explosion orbit more eccentric than the pre-explosion orbit was, or even leads to the break-up of the binary [22, 23]. However, this is not the only effect a supernova explosion has on the orbital elements of a binary.

The fact that many of the observed (isolated) radio pulsars and even a few BH-LMXBs have very high space velocities with respect to the galactic rotation [24, 25, 26] (among the pulsars up to $\sim 10^3 \mathrm{kms}^{-1}$) clearly indicates that in a core collapse supernova and the subsequent formation of a NS or a BH an additional huge momentum can be imparted to the compact star. Because neither the modulus nor the direction of this momentum can be predicted by theory, the effect of such a supernova kick is to essentially randomize the orbital elements of a binary in which such a supernova occurs. Thus the outcome of a binary evolution from a well-defined initial state beyond the first supernova explosion can only be determined in a statistical sense. What has to be done in practice is to assume a particular momentum distribution, e.g. chosen such as to best reproduce the observed distribution of the space velocities of radio pulsars [24], and a random orientation of the momentum vector.

DIFFERENCES BETWEEN LMXBS AND CVS

Although LMXBs and CVs are superficially similar, LMXBs differ in a number of ways from CVs and so does probably also their evolution. One of these differences we have just noted: supernova explosions and supernova kicks which are unavoidable in the formation of LMXBs but do not occur at all in the formation of CVs. Among the other important differences we note the following:

The mass of the accretor

The average mass of a NS ($\sim 1.4 M_\odot$) is about 2.5 times larger than that of an average WD ($\sim 0.6 M_\odot$) and the mass of a typical stellar mass BH ($\sim 5 - 15 M_\odot$) is even bigger. Therefore, stable mass transfer in LMXBs is possible with correspondingly more massive donor stars. In BH-LMXBs even intermediate mass donor stars are possible as e.g. in V4641 Sgr, V1033 Sco and IL Lup [3]. This in turn means that nuclear evolution of the donor star as a driving mechanism of mass transfer is much more important than in CVs. Furthermore, in BH-LMXBs with an intermediate mass donor even stable thermal time scale mass transfer is possible if the donor has evolved beyond the terminal age main sequence, as is the case in V1033 Sco (see e.g. [27]).

On the other hand, for given donor mass M_2 the mass ratio M_1/M_2 is systematically larger in a LMXB than in a CV. Therefore mass transfer is more stable which means that for a given angular momentum loss rate $\dot{J}$ or rate of expansion of the donor $\dot{R}_2$ due to nuclear evolution the resulting mass transfer rate is lower. On top of that we note that with increasing mass ratio gravitational radiation [18] as well as magnetic braking according to [9, 10] become less efficient.

Furthermore, for a given donor radius R_2 the corresponding Roche radius of the primary and with it the outer radius of the accretion disc grow with the mass ratio, i.e. are systematically larger in LMXBs than in CVs. This, together with the tendency to reduced mass transfer leads to an increased tendency for the occurrence of disc instabilities, i.e. for LMXBs to be transients [4].

The gravitational binding energy at the "surface" of the accretor

A direct consequence of the fact that the gravitational binding energy at the surface of a NS or at the innermost stable circular orbit of a BH is of the order of 100 MeV/nucleon, i.e. ~ 1000 times larger than the corresponding value for a WD is that the accretion luminosity per unit mass accreted is higher by a factor ~ 1000 in LMXBs than in CVs, and that in LMXBs the bulk of the energy emerges as (hard) X-rays whereas in CVs most of the energy emerges as (far) UV and optical radiation. As a consequence of the much higher accretion luminosities generated in LMXBs and of the fact that the emitted radiation is much harder, i.e. more penetrating, irradiation by accretion luminosity of the other components of a LMXB, i.e. of the donor star and the accretion disc becomes an important issue.

Irradiation of the accretion disc

Irradiation of the outer parts of the accretion disc by accretion luminosity emerging from the vicinity of the compact star plays an important role in LMXBs. On the one hand, as was first noted by [28], irradiation of the disc makes LMXBs visually much brighter than what one would expect based on viscous heating of the disc alone. On the other hand, irradiation of the disc allows for stationary accretion in systems which would otherwise be transient and undergo dwarf nova-like outbursts [29]. Even more important are the consequences which irradiation has for the properties of transient systems [29, 30]. Irradiation results in much longer outbursts, with higher accretion rates that can easily exceed the Eddington limit of the compact star. During an outburst the irradiated parts of the accretion disc are essentially emptied. As a consequence, the duration of the quiescence during which the disc is refilled also lasts much longer. Thus it is irradiation of the accretion disc which is to a large extent responsible for the characteristics of transient LMXBs. We note however, that other factors such as disc evaporation [30, 31] during quiescence also have an important influence on the outburst behaviour of X-ray transients.

Irradiation of the donor star

That irradiation of the donor star by accretion luminosity might drastically change the long-term evolution of LMXBs was first suggested in [32]. A detailed yet still simplified analysis [33, 34, 35, 36] shows that in semi-detached compact binaries (i.e. LMXBs and CVs), where the donor is irradiated by accretion luminosity, mass transfer could proceed through a limit cycle in which phases of irradiation-driven mass transfer alternate with phases during which mass transfer virtually stops, and in some cases the system even becomes detached. Whether or not this irradiation-driven feedback loop really works is currently unclear. Its occurrence depends on a free parameter which essentially measures the fraction of the accretion luminosity that is absorbed in the donor's photosphere. And the precise value of that parameter is strongly model-dependent and difficult to determine.

LESSONS FROM MS-PULSAR BINARIES

It is now widely accepted that NS-LMXBs are immediate progenitors of msPSR binaries (for a review see e.g. [37]). msPSR binaries are characterized by spin periods of the NS in the range $1.6\ \mathrm{ms} \lesssim P_{\mathrm{spin}} \lesssim 60\ \mathrm{ms}$, and orbital periods in the range $0.1^{\mathrm{d}} \lesssim P_{\mathrm{orb}} \lesssim 700^{\mathrm{d}}$ [38]. When compared with the observed ms-PSR binary "phase space" $(P_{\mathrm{orb}}, P_{\mathrm{spin}})$, we find that LMXBs with known $(P_{\mathrm{orb}}, P_{\mathrm{spin}})$ [3] cover only a very small part of the pulsar "phase space", i.e. the LMXBs in question are all characterized by short orbital periods $P_{\mathrm{orb}} \lesssim 1^{\mathrm{d}}$ and the majority of them (11 out 12 systems) have very short spin periods $P_{\mathrm{spin}} \lesssim 5$ ms. Therefore, if LMXBs are progenitors of ms-PSR binaries with long orbital periods ($P_{\mathrm{orb}} \gtrsim 1^{\mathrm{d}}$) this means that *we do not see the progenitors of the msPSR binaries with long orbital periods ($P_{\mathrm{orb}} \gtrsim 1^{\mathrm{d}}$)*. One possbile reason for why this is so is that long-period LMXBs have very extended accretion discs and, therefore, are all transient X-ray sources [39]. Because of the large disc size and the effect of irradiation of the disc during an outburst, the outbursts during which the irradiated parts are practically emptied last very long. As a consequence of the almost complete depletion of the irradiated parts of the disc, the subsequent quiescence, during which the disc is refilled and the X-ray luminosity is very low, lasts very long too. Because of the small duty cycle (ratio of the duration of an outburst relative to the duration of a full outburst cycle) which gets smaller the longer the orbital period [39], and because of their very low X-ray luminosities during quiescence, such long-period transient X-ray binaries stand a very low chance of being detected either in outburst or during low state. Therefore, if this is the reason for why we do not see the progenitors of long-period msPSR binaries, this implies that *there exists a large hidden population of transient, long-period NS-LMXBs in quiescence* [39, 40]. Finally we note that an analogous argument applies also to long-period BH-LMXBs like V1487 Aql.

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