Chapter 11

Origin and evolution of X-ray binaries

11.1 Formation and evolution of high-mass X-ray binaries

The observed presence of a neutron star in a binary poses the following problem. According to the theory of stellar evolution, it is always the more massive star in a binary that explodes first as a supernova. According to eq. (10.3) this means that the binary is disrupted ($e > 1$) by the supernova explosion, unless the masses of the two stars are very close to one another (more specifically: $M_1 > M_2 > M_1 - 2M_{\rm NS}$, where $M_{\rm NS}$ is the mass of the compact remnant, i.e. the neutron star). One therefore does not expect to find (many) binaries with a neutron star. Two possible solutions have already been discussed in Sect. 10.1: the supernova can occur at apastron of an eccentric orbit (eq. 10.12) and the new neutron star may be born with a kick velocity (eq. 10.14). Most important, however, is the possibility that the more massive star becomes the less massive star before it explodes as a result of mass transfer. We discuss three scenarios for this.

11.1.1 Origin of the Be X-ray binaries: pre-supernova case B mass transfer

The evolution of a massive binary into a Be/X-ray binary is illustrated in Figure 11.1. In this example a binary starts out with 12 and 8 $M_\odot$, and an orbital period $P_{\rm orb} = 50$ days. The 12 $M_\odot$ star evolves first and expands after it exhausts its hydrogen, filling its Roche lobe when it crosses the Hertzsprung gap (Fig 11.1b). The binary thus evolves according to Case B, see Sect. 8.2. Since the more massive star still has a radiative envelope at this point, and the mass ratio is not far from unity, mass transfer may be conservative as has been assumed in this example. The orbital period decreases until the masses are equal (Fig 11.1c) after which the orbit expands. Mass transfer occurs on the thermal timescale of the donor star until almost the entire envelope has been transferred to the companion star; only then does the equilibrium radius of the donor star become smaller than its Roche lobe (Sect. 8.2). The 8 $M_\odot$ star has gained appreciably in mass, and rotates rapidly, due to the accretion of angular momentum with the mass. The result of the first phase of mass transfer is a binary in which the almost naked helium core of the initially more massive star is in a wide orbit around an Oe or Be star companion.

The core continues its evolution, and after a short time explodes as a supernova, leaving a neutron star of 1.35 $M_\odot$ (Fig. 11.1e). The sudden mass loss leads to an eccentricity of $e = 0.08$ and a velocity of the center of mass of the new binary of $v_s = 5.9$ km/s for an assumed symmetric explosion, according to eqs. (10.3–10.4). The neutron star may catch matter from the dense equatorial wind of the Be star and appear as an X-ray source. The wind of the Be star, too, often is transient; thus the binary is often a transient source of hard X-rays. The Be stars in Be X-ray binaries have inferred masses between 8 and 20 $M_\odot$. The upper limit is thought to be due to a selection effect: more massive stars have such strong winds that their rotation slows down quickly, and they cease having the strong equatorial outflows characteristic of Be stars. Accretion from the fast and tenuous winds of O stars is much less efficient,

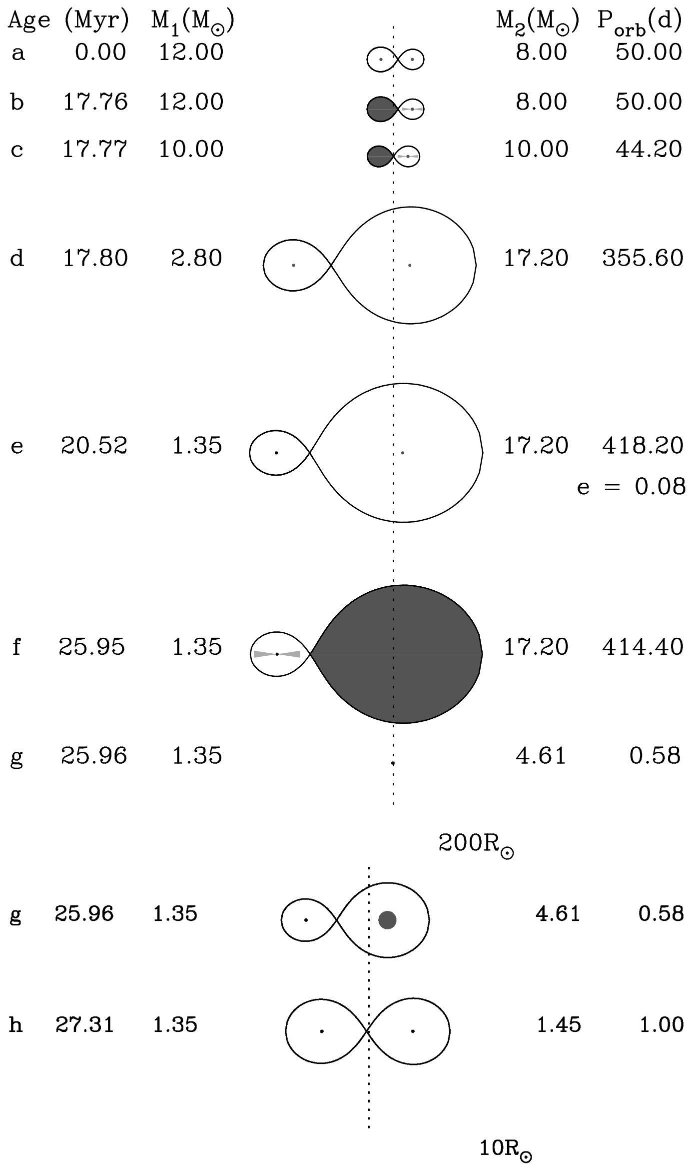

Figure 11.1. Conservative evolution of high-mass binary into a Be X-ray binary, and then into a binary radio pulsar. For explanation see text. Note the change of scale at phase g.

and does not produce a strong X-ray source unless the orbital period is $\lesssim 10$ days.

In early computations of binary evolution it has mostly been assumed that the helium core unwrapped by mass transfer evolves pretty much in the same way as it would have done inside the whole star. By computing the evolution of unwrapped cores explicitly several authors have shown that this assumption is not correct. In particular, even the cores of very massive stars, which would have evolved into a black hole inside the full star, can evolve into a neutron star instead when the star loses its envelope at an early evolutionary stage, due to the strong Wolf-Rayet mass loss of such exposed cores. This explains why no Be X-ray binary (formed via case B mass transfer) contains a black hole. An important consequence is that one can no longer transfer conclusions about the progenitor mass of a black hole from single-star evolution to binary evolution or vice versa.

Evolution into high-mass binary pulsars Overflow via the inner Lagrangian point starts when the companion reaches its Roche lobe (Fig 11.1f). The extreme mass ratio almost certainly causes the mass transfer to be dynamically unstable as the orbit shrinks rapidly (see eq. 7.9), and the neutron star eventually will plunge into the envelope of its companion. In the case shown in Figure 11.1, the spiral-in leads

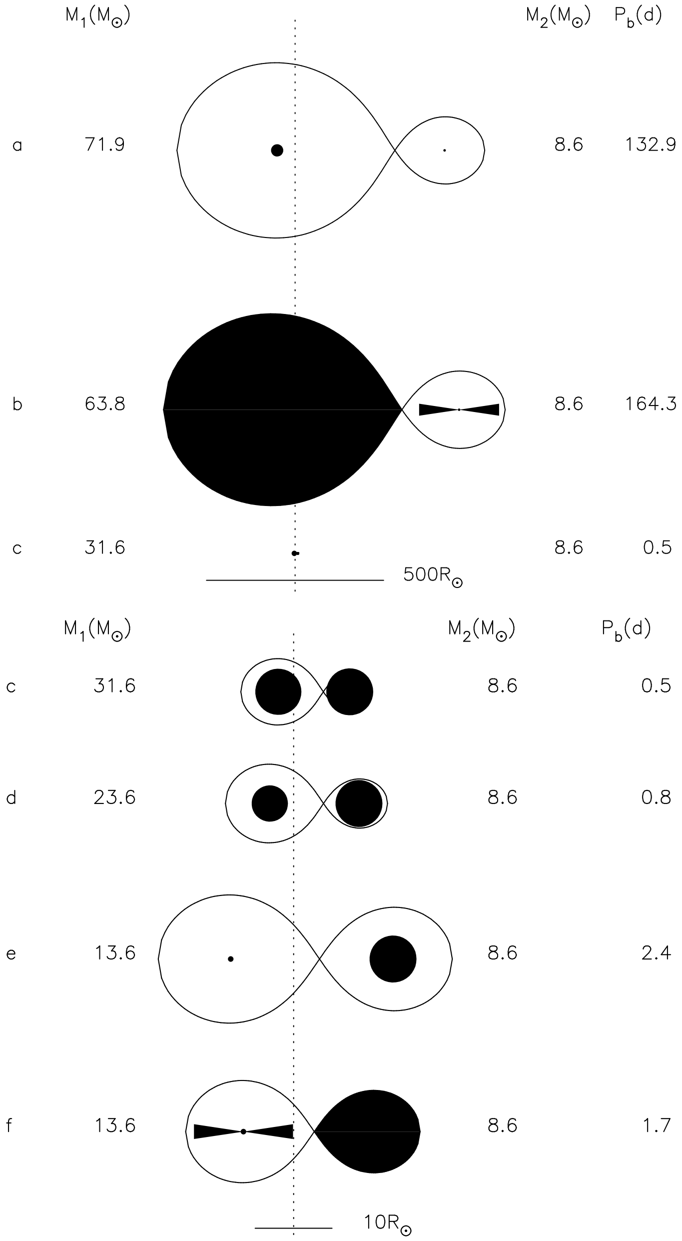

Figure 11.2. Drawing – to scale – of the evolution of a high-mass binary with a close initial orbit. For explanation see text; note the change in scale at phase c. The 8.6 $M_{\odot}$ star in phase c only barely fits in its Roche lobe. The final binary is modelled on LMC X-3.

to a very close binary consisting of the neutron star and the core of the Be star (Fig. 11.1g). If the helium core has too low a mass to evolve into a supernova, it will cool into a white dwarf, and the resulting binary looks like the one in which PSR 0655 + 64 is accompanied by a relatively massive white dwarf. In that case, the orbit retains the circular shape it obtained during spiral-in. Alternatively (as shown in Fig. 11.1h), continued evolution of the core leads to a second supernova explosion, which may lead to the formation of a high-mass radio pulsar binary like PSR 1913 + 16, consisting of two neutron stars in an eccentric orbit; or which may disrupt the binary. In the example shown, a symmetric explosion would disrupt the binary and a suitably aimed kick velocity is needed to produce a binary pulsar.

11.1.2 Origin of the supergiant X-ray binaries: case A mass transfer or spiral-in

Two very different scenarios have been discussed to explain the existence of the ‘standard’ high-mass X-ray binaries with a supergiant companion in a close orbit. The first scenario is similar to the one sketched above for the Be/X-ray binaries, involving (quasi)conservative mass transfer. Three effects conspire to keep the orbital period much shorter than in a Be/X-ray binary. First, the ratio of core mass to envelope mass increases with stellar mass (according to eq. 8.1) so that in a more massive binary relatively less mass is transferred, which results in less orbital expansion after conservative mass transfer (see Exercise 8.3). Second, many supergiant X-ray binaries are thought to originate from case A instead of case B, with initially very close orbits. This also explains that a neutron star can be accompanied by a very massive donor, as in the case of the binary Wray 977, in which a 48 $M_{\odot}$ star transfers mass to a neutron star: such a binary can form by conservative case A mass transfer even if the progenitor of the neutron star had an initial mass as low as 25 $M_{\odot}$. Third, and in contrast, substantial loss of mass and angular momentum during case A mass transfer is needed to explain the properties of some neutron-star supergiant binaries with $P_{\rm orb} < 10$ days.

The alternative scenario involves a massive and initially very wide binary that undergoes dynamically unstable case C mass transfer. This brings the mass-receiving star inside the envelope of the donor star and initiates a common envelope event (Sect. 10.2). Friction then transfers angular momentum and energy from the orbital motion to the envelope of the mass donor. As a result, the orbit shrinks dramatically, until the envelope is heated so much that it escapes, leaving the core of the donor in orbit around the mass-receiver, or until both stars merge completely. This spiral-in process happens so rapidly, that the mass receiving star accretes only a tiny fraction of the envelope of the donor.

This scenario is discussed especially to explain the formation of black-hole high-mass X-ray binaries such as LMC X-3, as illustrated in Fig. 11.2. The more massive star of the binary loses some mass in a stellar wind before it fills its Roche lobe. The mass transfer is unstable, and a spiral-in ensues, bringing the core of the donor in close orbit around the virtually unchanged receiver (see eq. 10.20; phases b-c in Fig. 11.2). The donor only fits inside its Roche lobe because stars in the LMC, due to their lower metallicity, are smaller at the same mass than stars in our Galaxy. The core loses some more mass in stellar wind as it evolves to a supernova, and forms a black hole (Fig. 11.2c-e).

11.2 Formation of low-mass X-ray binaries

The problem in producing a high-mass X-ray binary, i.e. avoiding a disruption of the binary during the supernova event, holds even more for the low-mass X-ray binaries. Mass loss via a wind of a massive star will not bring its mass below the $1 M_{\odot}$ of a low-mass companion. In order to keep the binary intact, one may have to invoke both a spiral-in phase and a rightly aimed kick velocity of the newly born compact star. An alternative that has been in vogue during the past few years is a quiet supernova explosion, when a white dwarf is pushed over the Chandrasekhar limit and implodes. Yet another alternative is evolution of a multiple system of three or more stars.

11.2.1 Origin of low-mass X-ray binaries via spiral-in

The spiral-in scenario was suggested first by van den Heuvel in 1983. Eqs. (10.20,10.21) show that the initial binary must have been rather wide if a merger is to be avoided. This allows both late case B (i.e. mass transfer starting when the donor is already a red giant with a convective envelope) or case C. To avoid a merger, case C mass transfer is preferred above case B, as the core mass will be higher and the envelope mass smaller. Consider for example a star just massive enough to evolve into a neutron star, with an initial mass of 11 $M_{\odot}$ which evolves a helium core of 2.5 $M_{\odot}$ on the giant branch (Fig. 11.3). A $1 M_{\odot}$ companion to this core fits within its Roche lobe provided the semimajor axis is larger than 3.3 $R_{\odot}$ (Fig. 11.3c). With eq. (10.20) and assuming $\alpha_{\rm CE}\lambda = 1$, we find that this requires a semimajor axis before spiral-in that is 430 $R_{\odot}$. An 11 $M_{\odot}$ star indeed expands to fill its Roche lobe in this binary during the first giant ascent before helium ignition, i.e. mass transfer is case B. The main-sequence star is hardly affected by the spiral-in process, and emerges pretty much as it entered.

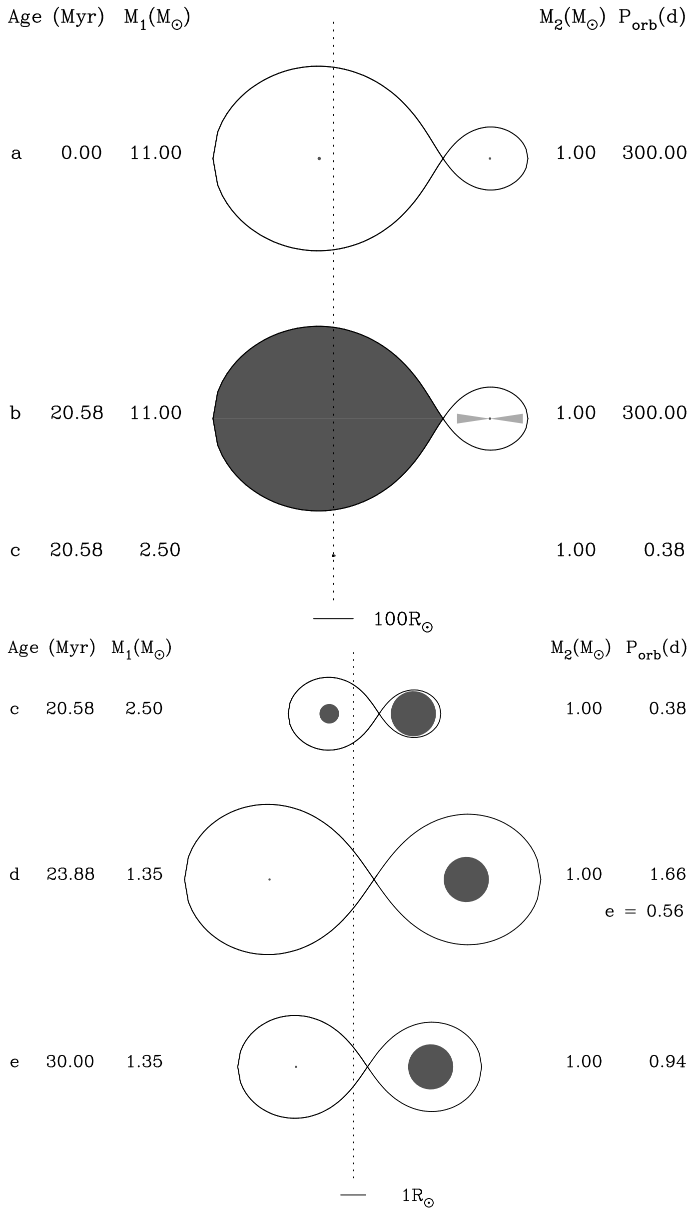

Figure 11.3. Evolution of a massive binary with an extreme mass ratio into a low-mass X-ray binary via a common envelope phase resulting in spiral-in, followed by the supernova explosion of the helium core of the massive star. For explanation see text. Note the change of scale at stage c.

The supernova explosion of the $2.5\,M_\odot$ helium core causes an eccentricity $e = 0.56$, if a $1.35M_\odot$ neutron star is formed without a kick velocity (Fig. 11.3d). Tides quickly circularize the binary so that it ends up with the low-mass star underfilling its Roche lobe by about a factor 2 (Fig. 11.3e). Angular momentum losses may then bring the $1M_\odot$ star in contact with its Roche lobe, provided the post-supernova orbit is not too wide (see Sect. 11.3). In a system with a longer orbital period, mass transfer can start only after the $1M_\odot$ star evolves away from the main sequence, and expands into a (sub)giant. The boundary between these two cases depends on the mechanism for loss of angular momentum.

Thus, the spiral-in scenario does allow the formation of low-mass X-ray binaries. However in reality the scenario is more complicated than sketched above. The crucial moment in the evolution is the moment of the supernova explosion. If the binary is to remain bound, not too much mass must be lost from the system with the explosion (see eq. 10.3). This may be the case if the core of the neutron star progenitor is not too massive, i.e. if the progenitor itself is not too massive, as in the example just described. However, such relatively low-mass helium stars expand and fill their Roche lobes again after exhausting helium in their centre, leading to a renewed phase of (unstable) mass transfer to the companion. Therefore either the initial orbit must be even wider, allowing two consecutive spiral-in phases, or the neutron-star progenitor must be more massive. In that case, a well-directed kick may help to keep the binary bound. Interestingly, collapse of a massive evolved core into a black hole may also make it easier for the binary to remain bound, as a smaller fraction of the mass is expelled in that case.

PSR 1820 – 11 has already been mentioned as a possible high-mass radio pulsar binary. The available observations also allow the companion to the pulsar to be a low-mass main-sequence star; if so, the binary would be a progenitor of a low-mass X-ray binary, along the scenario just sketched.

11.2.2 Origin via accretion-induced collapse

Accretion-induced collapse of a massive white dwarf as a mechanism for the formation of a neutron star was first suggested by Whelan & Iben in 1973. The progenitor of a massive white dwarf must have a mass close to those of direct progenitors of neutron stars. The close binary is therefore formed through a spiral-in, very similar to the spiral-in just described: however, the core that emerges from the spiral in now evolves into a massive white dwarf, and avoids the supernova explosion. When mass transfer is initiated, either by loss of angular momentum or by expansion of the secondary into a (sub)giant, the white dwarf accretes mass until it transgresses the Chandrasekhar limit, at which point it implodes. Little mass is lost in the implosion; most of the loss in fact may come from the change in binding energy, which is roughly:

$$\Delta M \approx \frac{3G{M_{\rm WD}}^2}{5R_{\rm NS}c^2} \approx 0.2 M_\odot \tag{11.1}$$

where $M_{\rm WD}$ is the mass of the white dwarf and $R_{\rm NS}$ the radius of the neutron star. The smaller mass loss makes it easier for the binary to survive the supernova explosion. It is often implicitly assumed that the kick velocity is also less for a neutron star formed by white dwarf collapse. As long as the mechanism causing the kick velocity is not known, however, there is no good reason for such an assumption.

Accretion-induced collapse as a mechanism to form a neutron star gained widespread recognition once it was realized that the magnetic field of the radio pulsar in old binaries was still in excess of 10^8G. Combined with the view that the magnetic field of a neutron star decays on a time scale of a few million years, this meant that there must be young neutron stars in old binaries: accretion-induced collapse can achieve this. It has recently become less clear, however, that the magnetic field of neutron stars does indeed decay so rapidly. In the absence of rapid decay of the magnetic field of neutron stars, there is no reason anymore to invoke accretion-induced collapse for the formation of low-mass X-ray binaries.

11.3 Evolution of low-mass X-ray binaries

By combining Kepler's law eq. (2.42) with an expression for the Roche-lobe radius, eq. (6.2), we get an approximate relation between the orbital period and the mass and radius of the Roche-lobe-filling star (see Exercise 6.2):

$$P_{\rm orb} \approx 0.35\,{\rm d} \left(\frac{R_{\rm d}}{R_\odot}\right)^{3/2} \left(\frac{M_{\rm d}}{M_\odot}\right)^{-1/2} \left(\frac{2}{1+q}\right)^{0.2} \approx 9.6\,{\rm hr} \left(\frac{R_{\rm d}}{R_\odot}\right)^{3/2} \left(\frac{M_{\rm d}}{M_\odot}\right)^{-1/2} (1+q)^{-0.2} \tag{11.2}$$

For low-mass donors, when $q \lesssim 0.7$, we can ignore the weak dependence on the mass ratio. Thus, by assuming a mass-radius relation for the donor star, we may determine its mass from the observed orbital period, as summarized in Table 11.1. In Fig 9.1 the known orbital periods for low-mass X-ray binaries are shown.

In stable mass transfer, the radius of the donor equals the radius of the Roche lobe at all times in this process, so that $R_{\rm L} = R_{\rm d}$ and $\dot{R}_{\rm L} = \dot{R}_{\rm d}$. The change in radius of the donor star may be due to internal

Table 11.1. Mass-radius relations and derived mass-orbital-period relations for low-mass X-ray binaries. Valid for donors in thermal equilibrium.

low-mass MS	$R_\mathrm{d}/R_\odot \approx M_\mathrm{d}/M_\odot$	$\zeta_\mathrm{eq} \approx 1$	$P_\mathrm{orb} \approx 9.6\,\mathrm{hr}\, M_\mathrm{d}/M_\odot$
low-mass He-MS	$R_\mathrm{d}/R_\odot \approx 0.2\, M_\mathrm{d}/M_\odot$	$\zeta_\mathrm{eq} \approx 1$	$P_\mathrm{orb} \approx 0.86\,\mathrm{hr}\, M_\mathrm{d}/M_\odot$
white dwarf	$R_\mathrm{d}/R_\odot \approx 0.0115\ (M_\mathrm{d}/M_\odot)^{-1/3}$	$\zeta_\mathrm{eq} = -\frac{1}{3}$	$P_\mathrm{orb} \approx 43\,\mathrm{sec}\,(M_\mathrm{d}/M_\odot)^{-1}$
low-mass red giant	$R_\mathrm{d}/R_\odot \approx 3500\ (M_\mathrm{c,d}/M_\odot)^4$	$\zeta_\mathrm{eq} \approx 0$	$P_\mathrm{orb} \approx 20\,\mathrm{d}\left(\frac{M_\mathrm{c,d}}{0.25 M_\odot}\right)^6 \left(\frac{M_\mathrm{d}}{M_\odot}\right)^{-1/2}$

evolution of the star, or to the mass-transfer process. Similarly, the change in the Roche radius may be due to the mass-transfer process or to the (spontaneous) loss of orbital angular momentum:

$$\frac{\dot R_\mathrm{d}}{R_\mathrm{d}} = \left(\frac{\dot R_\mathrm{d}}{R_\mathrm{d}}\right)_\mathrm{ev} + \zeta_\mathrm{eq}\frac{\dot M_\mathrm{d}}{M_\mathrm{d}} \qquad \text{and} \qquad \frac{\dot R_\mathrm{L}}{R_\mathrm{L}} = \left(\frac{\dot R_\mathrm{L}}{R_\mathrm{L}}\right)_\mathrm{aml} + \zeta_\mathrm{L}\frac{\dot M_\mathrm{d}}{M_\mathrm{d}} \tag{11.3}$$

where we have used the mass-radius exponents defined in Sect. 7.3. The term $(\dot R_\mathrm{L}/R_\mathrm{L})_\mathrm{aml} = \dot a/a = 2\dot J/J$ according to eq. (7.8) in the absence of mass transfer. Thus we can derive the mass transfer rate $-\dot M_\mathrm{d}$ as (remembering that $\dot M_\mathrm{d}$ is negative)

$$-\frac{\dot M_\mathrm{d}}{M_\mathrm{d}} = \frac{1}{\zeta_\mathrm{eq} - \zeta_\mathrm{L}}\left[\left(\frac{\dot R_\mathrm{d}}{R_\mathrm{d}}\right)_\mathrm{ev} - 2\frac{\dot J}{J}\right] \tag{11.4}$$

This equation shows that mass transfer may be driven by loss of angular momentum from the binary ($\dot J < 0$), or by expansion of the donor star ($\dot R_\mathrm{d} > 0$) due to, for example, the ascent of the donor on the (sub)giant branch, or due to irradiation of the donor. We discuss these possibilities in turn.

11.3.1 Evolution via loss of angular momentum

The low-mass X-ray binaries with orbital periods between 80 min and 10 h may have main-sequence donors with masses between $0.1 M_\odot$ and $1.0 M_\odot$, according to Table 11.1. The evolutionary time scales of such low-mass stars are very long (see eq. 6.5). Since these masses are less than the $1.4 M_\odot$ characteristic for a neutron star, the orbit of such a low-mass X-ray binary expands when mass is transferred conservatively from the donor (see eq. 7.9). Unless the donor star expands more than its Roche lobe, this expansion will put an end to the mass transfer. It appears then that angular momentum must be lost from the binary to keep mass transfer going. Two processes have been proposed to provide such orbital angular momentum loss.

Gravitational radiation It was realized by Kraft et al. in 1962 that gravitational radiation provides a sufficiently high loss of angular momentum to drive observable mass transfer in a close binary. According to general relativity the changing quadrupole moment of the orbiting bodies produces gravitational waves that carry energy and angular momentum from the orbit. The loss of angular momentum via gravitational radiation may be written, for a circular orbit:

$$-\left(\frac{\dot J}{J}\right)_\mathrm{GR} = \frac{32 G^3}{5 c^5}\frac{M_1 M_2 (M_1 + M_2)}{a^4} \tag{11.5}$$

(For an eccentric orbit, this should must be multiplied by a function of eccentricity.) The strong dependence on the size of the orbit (a^{-4}) means that this process is only effective in very close binaries: the timescale for angular momentum loss $\tau_\mathrm{GR} = -J/\dot J$ becomes comparable or shorter than the Hubble time if $a \lesssim 1\, R_\odot$.

Magnetic braking Single stars of spectral type F or later show signs of magnetic activity (such as starspots and X-ray emission) and their rotation is observed to slow down with age. This is interpreted as loss of angular momentum via their stellar winds. Even though the amount of mass lost in the wind is very small, the concurrent loss of angular momentum may be appreciable because the magnetic field of the star forces the wind matter to corotate to a large distance from the stellar surface. If the donor star in a close binary loses angular momentum in this way, it will not be able to rotate slower, as it is kept in corotation with the orbit by tidal forces. Thus loss of angular momentum is transferred from the donor rotation to the orbital revolution, i.e. the binary loses angular momentum.

The rate of angular momentum loss has been derived approximately as follows. Skumanich found in 1972 that the rotation velocities of single G stars decreases with age as $v_{\rm rot} \approx 5.0\,(t/{\rm Gyr})^{-0.5}$ km/s. Since $\dot{J} = I\dot{\Omega}$ and $v_{\rm rot} = \Omega R$, where Ω is the angular spin frequency of the star, and writing the moment of inertia as $I = k^2 M R^2$, the angular momentum loss should be

$$\dot{J} \approx -4 \times 10^{-29}\,{\rm s/cm^2} \times k^2 M R^4 \Omega^3 \tag{11.6}$$

in cgs units, with $k^2 \approx 0.1$ for a low-mass main-sequence star. In a tidally locked binary, Ω equals the the orbital angular frequency $2\pi/P$. Using Kepler's law we can then write the orbital angular momentum loss due to magnetic braking as

$$-\left(\frac{\dot{J}}{J}\right)_{\rm MB} \approx 4 \times 10^{-30}\,{\rm s/cm^2} \times \frac{G(M_1+M_2)^2 R_1^4}{M_2\,a^5} \tag{11.7}$$

According to this formula angular momentum loss due to magnetic braking increases strongly with decreasing separation, due to its strong dependence on stellar rotation rate. However, this result relies on extrapolating the Skumanich relation to much faster rotation rates than it has been measured for (up to about 30 km/s). Recent indications are that the magnetic field generated by stellar dynamos saturates at $\Omega \gtrsim 10\Omega_\odot$, and therefore magnetic braking is probably (much) weaker at the rotation rates found in close binaries than implied by eq. (11.7).

By equating the loss of angular momentum with one or both of the mechanisms discussed above, we may use eq. (11.5) to calculate the evolution of a low-mass X-ray binary. Mass-transfer rates can be calculated this way for main-sequence stars, with $\zeta_{\rm eq} = 1$, and for white-dwarf donor stars, with $\zeta_{\rm eq} = -1/3$. If we assume the total mass of the binary to be conserved, then $\zeta_{\rm L}$ is given by eq. (7.22).[1] The results are shown in Figure 11.4, for angular momentum loss due to the emission of gravitational radiation only (eq. 11.5), and for the three types of donors given in Table 11.1, i.e. stars on the main sequence, stars on the helium main sequence, and white dwarfs.

For stars on the main sequence, the mass-transfer rate is about $\dot{M} \approx 10^{-10}\,M_\odot$/yr, for donor masses between 0.2 and 1 $M_\odot$. Stars on the helium main sequence are smaller, and fill their Roche lobes in more compact binaries, leading to higher mass-transfer rates. Consider a main-sequence donor star. The mass transfer causes this star to become less massive, and the binary thus evolves towards shorter periods. At some point, the mass of the donor becomes too small to sustain significant hydrogen burning, and the core becomes degenerate. At this point, which is reached for a donor mass of about $0.08M_\odot$, further mass loss of the donor causes it to expand. The orbit expands with it, according to eq. (11.2). Thus, the evolution of the orbital period passes through a minimum. Detailed calculations show that this minimum may be identified with the cutoff at around 80 min observed in the period distribution of cataclysmic variables.

A similar line of reasoning shows that binaries with donors that initially burn helium must also show a minimum period, which detailed calculations put at around 10 min.

The minimum period for a binary whose donor is a main-sequence star depends on the chemical composition of the core of this star. If its helium abundance is higher, the star is relatively more compact,

[1]Extension to the more general case is straightforward, using eq. (7.14) in combination with eq. (6.2).

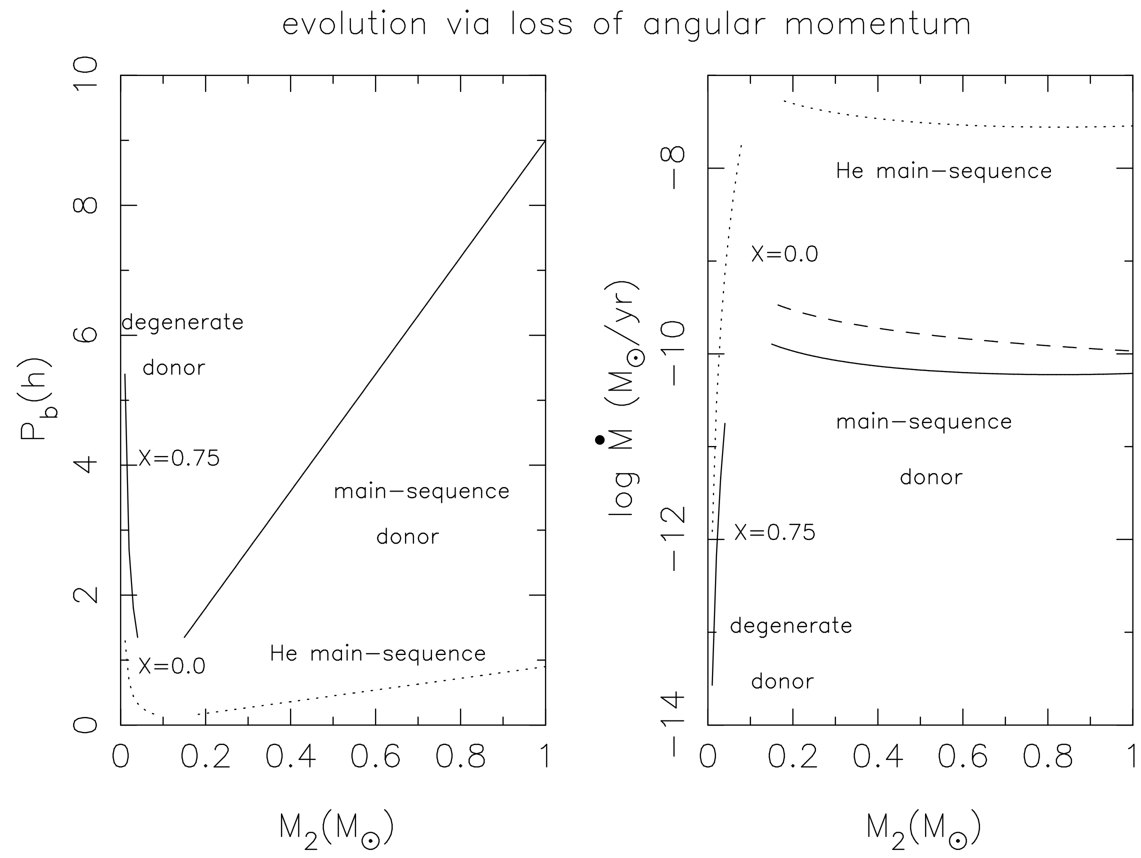

Figure 11.4. Orbital period and mass-transfer rate as a function of donor mass M_2, for binary evolution driven by loss of angular momentum via gravitational radiation. For degenerate donors (shown for $M_2 < 0.15M_\odot$; solid and dashed lines for the indicated values of the hydrogen abundance) the orbital period increases and the mass-transfer rate drops precipitously, as the donor mass decreases. For main-sequence donors (shown for $M_2 > 0.15M_\odot$; solid and dashed line for stars on the hydrogen and helium main sequence, respectively) the orbital period decreases and the mass-transfer rate hardly changes, as the donor mass decreases. The mass-transfer rates shown all assume $M_1 = 1.4M_\odot$, except for the dashed line, which assumes that the mass receiver is a 7 $M_\odot$ black hole.

and becomes degenerate at a smaller radius. Thus, such binaries may evolve to periods shorter than 80 min. A main-sequence star with a helium-enriched core may be formed when the donor starts transferring mass to its companion near the end of its main sequence life. The mass loss stops further evolution of this donor star, which reverts to the main sequence, but with an enhanced He abundance in the core.

A number of low-mass X-ray binaries have X-ray luminosities well in excess of 10^{36} ergs, and hence mass accretion rates well in excess of 10^{-10} $M_\odot$/yr, according to eq. (9.1). The orbital periods of several of these systems are too long for helium-burning donor stars, and more indicative of main-sequence donors. If one assumes that the currently observed $\dot{M}$ is also indicative of the $\dot{M}$ averaged over the time scale on which the binary evolves, such high mass-transfer rates require explanation. As suggested by eq. (11.4), any additional mechanism of loss of angular momentum increases the mass-transfer rate, and this has been the main reason to investigate mechanisms such as magnetic braking. The rate of angular momentum loss implied by eq. (11.7) is sufficiently high to explain the high observed values for mass-transfer rates in low-mass X-ray binaries and, less accurately, in cataclysmic variables. While magnetic braking is an attractive possibility to explain mass-transfer rates $\dot{M} \gtrsim 10^{-9}$ $M_\odot$/yr in low-mass X-ray binaries with main-sequence-like donor stars, the details and actual efficiency of this process are not well understood. Furthermore, it is worthwhile to remark that many X-ray binaries have shown appreciable variability already during the few decades that X-ray observations have been possible, and to stress that therefore it is not possible to determine the long-term averaged values of $\dot{M}$. Therefore the importance of magnetic braking in driving mass transfer in compact binaries has not been well-established.

11.3.2 Evolution via donor expansion

A number of low-mass X-ray binaries, including the well-known systems Sco X-1 and Cyg X-2, have orbital periods in excess of 0.5 days, indicating that their donor stars are (sub)giants (see Fig. 9.1). In these systems, mass transfer is driven by the evolutionary expansion of the donor star. The radius and luminosity of a low-mass giant are determined mainly by its core mass (see Fig. 6.3). Results of detailed calculations can be approximated by the core-mass radius relation given in Table 11.1, or more accurately with simple polynomial relations in $y \equiv \ln M_c/0.25M_\odot$:

$$\ln(R_\mathrm{d}/R_\odot) = a_0 + a_1 y + a_2 y^2 + a_3 y^3 \tag{11.8}$$

$$\ln(L_\mathrm{d}/L_\odot) = b_0 + b_1 y + b_2 y^2 + b_3 y^3 \tag{11.9}$$

The values of the fitting constants a_i, b_i depend on the metallicity of the star, and are given for two metallicities, for stars in the Galactic disk, and for stars in low-metallicity globular clusters, in Table 11.2.

The luminosity on the giant branch is almost completely due to hydrogen shell burning, and is related to the core mass M_c by

$$\dot{M}_c \approx 1.37 \times 10^{-11} \left(\frac{L}{L_\odot}\right) M_\odot/\mathrm{yr} \tag{11.10}$$

Combining eqs. (11.8) and (11.10) gives the relation between the change in radius and the change in core mass:

$$\frac{\dot{R}_\mathrm{d}}{R_\mathrm{d}} = [a_1 + 2a_2 y + 3a_3 y^2]\frac{\dot{M}_c}{M_c} \tag{11.11}$$

In the absence of loss of angular momentum, eq. (11.4) may be rewritten

$$-\frac{\dot{M}_\mathrm{d}}{M_\mathrm{d}} = \frac{1}{\zeta_\mathrm{eq} - \zeta_\mathrm{L}} \left(\frac{\dot{R}_\mathrm{d}}{R_\mathrm{d}}\right)_\mathrm{ev} \tag{11.12}$$

which completes the set of equations required to calculate the binary evolution. The orbital period and the two masses determine the radius of the giant via eq. (11.2) and hence its core mass via eq. (11.8); the core mass determines the rate of radius expansion via eq. (11.11), and with this the mass-transfer rate via eq. (11.12). Thus the evolution can be calculated without resort to complete stellar evolution codes.

The results are shown in Figure 11.5 for $Z = 0.02$, the metallicity of ordinary disk stars. It is seen that there is a strong correlation between orbital period and mass-transfer rate: in a binary with a long orbital period, only a large giant fills its Roche lobe, and a large giant evolves more rapidly.

The simple calculations hold for stars beyond the subgiant branch; for subgiants, eq. (11.10) does not apply. Eqs. (11.8) and (11.9) are valid for giants at thermal equilibrium. Detailed calculations show that this is a good approximation until the donor envelope has been almost fully exhausted.

Table 11.2. Constants for the fits to the core-mass - radius and core-mass - luminosity relations for low-mass giants, according to Webbink, Rappaport, & Savonije (1983).

	a_0	a_1	a_2	a_3	b_0	b_1	b_2	b_3	mass range
$Z = 0.02$	2.53	5.10	-0.05	-1.71	3.50	8.11	-0.61	-2.13	$0.16 < M_c/M_\odot < 0.45$
$Z = 0.0001$	2.02	2.94	2.39	-3.89	3.27	5.15	4.03	-7.06	$0.20 < M_c/M_\odot < 0.37$

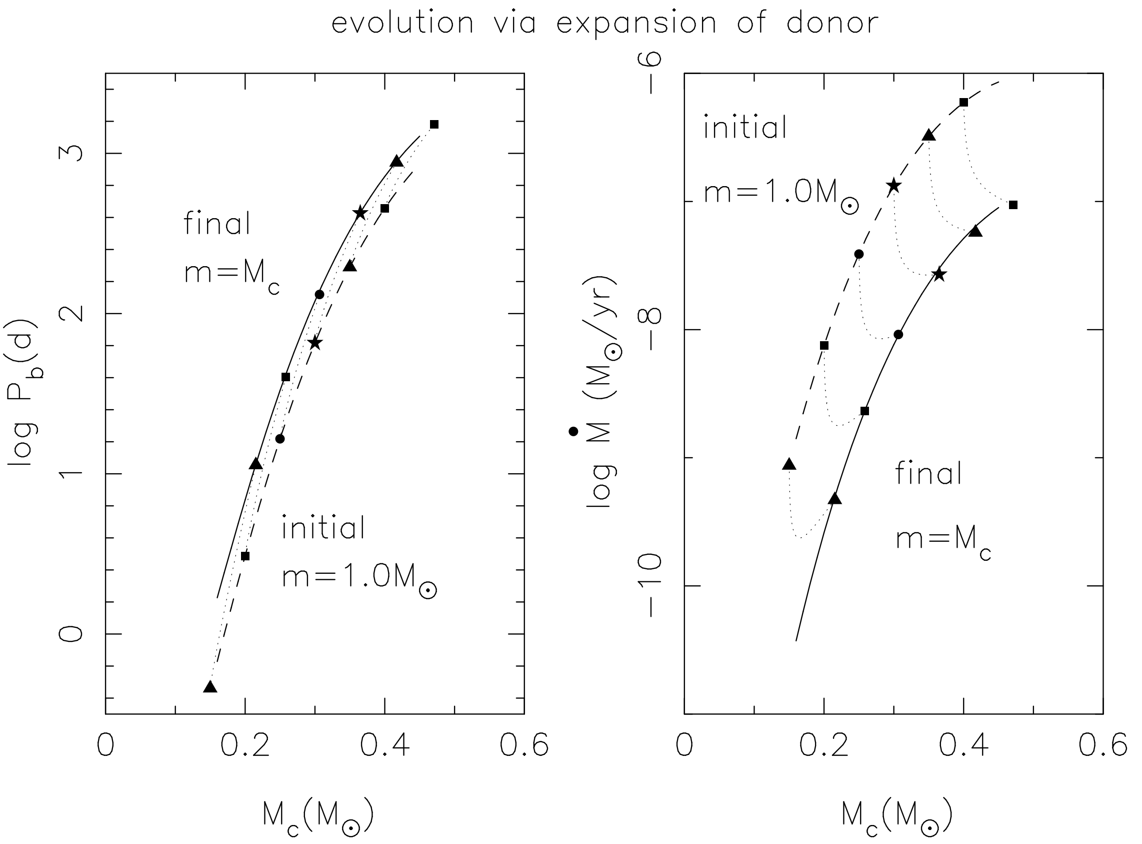

Figure 11.5. Orbital period and mass-transfer rate as a function of the mass of the donor core M_c, for binary evolution driven by expansion of a giant donor star. The mass-transfer rates shown all assume $M_1 = 1.4M_\odot$ and $\dot{M}_1 = -\dot{M}_2$.

11.3.3 Origin of low-mass binary radio pulsars

The evolutionary scenario for low-mass X-ray binaries with (sub)giant donors received strong confirmation with the discovery of radio pulsars in circular orbits with a very low mass-function, and hence a probable companion mass of $0.2 - 0.4M_\odot$ listed as low-mass binary radio pulsars in Table 9.5. The scenario discussed in the previous subsection automatically leads to such a binary: once the envelope of the giant donor is exhausted, the giant's core remains and cools into a white dwarf. The orbital period of the current binary sets the radius of the giant immediately prior to the end of mass transfer, and thus its core mass. Thus, the orbital period P_b of the radio pulsar should be correlated to the mass M_{wd} of its white-dwarf companion. Approximately (from Table 11.1):

$$P_{\rm orb} \approx 40\,{\rm days} \left(\frac{M_{\rm wd}}{0.25M_\odot}\right)^{5.5} \qquad (11.13)$$

valid for for circular orbits with $P_b \gtrsim 20\,$days.

The low eccentricity of the orbits of low-mass binary radio pulsars indicates that orbital circularization must have occurred following the formation of the neutron star. The low mass-functions indicate white dwarf companions to the radio pulsars with masses lower than the $\approx 0.6M_\odot$ expected for a white dwarf evolved from a single star. Both these observations are explained by the scenario in which a giant fills its Roche-lobe — causing strong tidal forces and hence rapid circularization, and transfers its envelope to the neutron star — thereby cutting off the growth of its core. The mass transfer also explains the short pulse period of the radio pulsars in these binaries as a consequence of the spin-up of the neutron star as it accretes mass from an accretion disk.

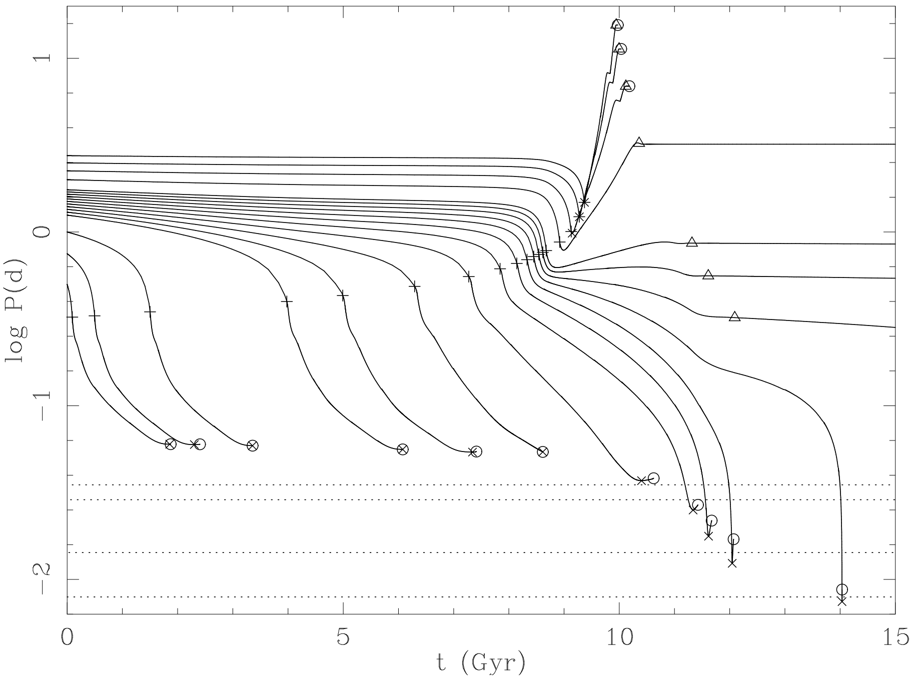

Figure 11.6. Evolution of the orbital periods of low-mass X-ray binaries with an initial donor mass of 1.0 $M_\odot$ and selected initial periods between 0.5 and 2.75 days. The curves show the results of detailed evolution calculations including angular momentum loss by gravitational radiation (eq. 11.5) as well as magnetic braking (eq. 11.7). The initial composition has $Z = 0.01$. The symbols mark special points in the evolution: + marks the start of Roche-lobe overflow (RLOF), × the minimum period, △ the end of RLOF and ○ marks the end of the calculation. The four dotted horizontal lines show the orbital periods of the closest observed LMXBs in globular clusters: 11.4 and 20.6, and in the galactic disk: 41 and 50 minutes.
Systems with initial periods below the bifurcation period of about 1.5 days evolve to smaller orbital periods due to angular momentum loss (dominated by magnetic braking in this case) and mostly reach a minimum period of ≈ 70 min. Initially wider systems are dominated by nuclear expansion after the main sequence and evolve to longer periods. Systems with periods just below the bifurcation period develop helium-rich cores and can reach a minimum period as short as 10 min; however this requires strong fine-tuning of the initial period.

Interestingly, the realization that rapidly rotating radio pulsars may emerge from low-mass X-ray binaries came with the discovery of a single radio pulsar, PSR1937 + 21. Its extremely rapid rotation can be understood as the consequence of accretion of a substantial amount of mass $\gtrsim 0.1 M_\odot$ from an accretion disk, by a neutron star with a low magnetic field. The magnetic field of PSR1937 + 21 is indeed low (see Table 9.5). In order to explain the absence of any companion, several destruction mechanisms were suggested. Detailed scrutiny of these mechanisms showed that none of them are convincing. The discovery of another millisecond pulsar brought a more likely solution: PSR1957 + 20 is heating its companion enough to evaporate it.

11.3.4 Recent developments

Three recent developments are changing our picture of the low-mass X-ray binaries. First, it has been found that several low-mass X-ray binaries have donors with masses that aren't as low (viz. $\leq 1 M_\odot$) as hitherto assumed for low-mass X-ray binaries. For example, the black-hole binary GRO J 1655 − 40 has donor with a mass of about $2.3\,M_\odot$. It would appear that the donor must be a subgiant to fill its Roche lobe in the 2.6 d orbit. However, accurate radius determinations of main-sequence stars in double-lined eclipsing binaries show that stars with masses in the range 2-4 $M_\odot$ expand sufficiently on the main-sequence to explain mass transfer from a main-sequence star in GRO J 1655 − 40.

Secondly, the observation of black-hole binaries in low-mass systems with evolved donors implies that there are many times more – in the ratio of the main-sequence life time to the giant life time, i.e. a factor ∼ 100 – black hole binaries with an unevolved companion which does not fill its Roche lobe. This has obvious consequences for the estimated birth rate of black-hole binaries.

And finally, the Wide Field Camera on board of the BeppoSAX X-ray satellite has discovered relatively dim X-ray transients, with peak luminosities $\leq 10^{37}$ erg/s, thanks to its unique combination of a large field of view and small angular separation. Most of these dim transients are bursters, i.e. neutron stars, which confounds the recent speculations that the vast majority of X-ray transients with low-mass donors are black hole systems.

Exercises

11.1 Consider the low-mass X-ray binary V4134 Sgr listed in Table 9.4. In this exercise, assume that the X-ray source is a neutron star (with $M = 1.4\,M_\odot$ and $R = 10\,\mathrm{km}$) and that the measured X-ray luminosity is the total accretion luminosity. Also assume the mass of the binary is conserved during mass transfer.

(a) Use the observed properties to compute the mass transfer rate in this system.

(b) Consider the orbital period of V4134 Sgr. Without doing any actual calculations, argue which of the following processes could be responsible for driving mass transfer in this system:

– nuclear expansion of the donor
– orbital angular momentum loss by gravitational radiation
– orbital angular momentum loss by magnetic braking
– exchange of orbital and spin angular momentum by tidal interaction.

(c) Compute the expected mass transfer rate if mass transfer is driven by (1) gravitational radiation, and (2) by magnetic braking. Compare your answers to the result you obtained for (a): which process is most likely to drive the observationally inferred mass transfer rate?

11.2 Now consider the low-mass X-ray binary Sco X-1, again referring to Table 9.4. Make the same assumptions as in exercise 11.1.

(a) Consider the various types of donor star summarized in Table 11.1. Which of these are possible donors of Sco X-1?

(b) Assume from now on that the donor is (just) on the red giant branch and has a mass of $1.0\,M_\odot$. Compute the expected mass transfer rate from nuclear expansion of the donor, and compare to the mass transfer rate inferred from its observed X-ray luminosity.

Note: instead of eqs. 11.8–11.9, you may also use the simpler (somewhat less accurate) relations between core mass, radius and luminosity given in Table 11.1 and

$$\frac{L}{L_\odot} = 2.3 \times 10^5 \left(\frac{M_c}{M_\odot}\right)^6$$

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