Chapter 1

Introduction and summary

1.1 The evolution of single stars

Stars are formed in clouds that are predominantly found in the spiral arms of galaxies. If such a cloud contracts, its temperature rises and it fragments into several hot cores. Such a condensation contracts in its turn, until the circumstances in its centre allow hydrogen fusion to take place. The condensation has become a zero-age main-sequence star and the mass and composition of the young star determine how it will spend the rest of its life.

The main sequence is the longest phase in the active evolution of a star (about 80%), so that most stars we observe are main-sequence stars. During this phase the luminosity and surface temperature of the star change only little, but when the star runs out of hydrogen in its core, it will change drastically. Because the core consists of helium only, nuclear fusion stops and the helium core will contract and heat up. The hydrogen-rich layers just outside the core become sufficiently compressed and heated that hydrogen fusion can take place in a shell around the core. The hydrogen-burning shell converts hydrogen into helium, and the core becomes more massive, more compact and hotter. Calculations show that a more compact core causes the density in the burning shell to drop so that the density in the envelope must drop as well to maintain hydrostatic equilibrium. The envelope of the star expands and cools, so that the opacity in the envelope rises and the envelope becomes convective. The star becomes a red giant and keeps expanding as long as the helium-core mass grows and becomes more compact. Because red giants are luminous and the surface gravity is low, they are thought to have strong stellar winds that blow appreciable amounts of gas into the interstellar medium, although the exact mass-loss rates due to stellar wind are unknown.

For all stars that evolve within a Hubble time ($M \gtrsim 0.8\,M_{\odot}$) the core pressure and temperature become sufficiently high to start helium fusion. In the case of stars with masses $\lesssim 2.4\,M_{\odot}$ the helium core is degenerate, therefore isothermal and the core grows up to $0.47\,M_{\odot}$ before helium is ignited. Because the core is degenerate, the rise in temperature due to the helium fusion does not lead to a rise in pressure and density, so that a thermonuclear runaway ensues, in what is called the 'helium flash', until the rising temperature eventually lifts the degeneracy. The helium cores in stars more massive than $2.4\,M_{\odot}$ are non-degenerate, so that helium fusion begins at a lower helium-core mass, hence a smaller radius, and without a helium flash. These stars ascend the red-giant branch only little and as a consequence lose relatively little mass in a stellar wind at this stage.

While helium is ignited in the core, the core expands and as a consequence the star shrinks again. The star is now on the horizontal branch until all helium has been converted to carbon and oxygen and the star expands again. Stars more massive than about $10\,M_\odot$ can have many burning phases in which they produce increasingly more massive elements, until their core consists of iron and further nuclear fusion no longer releases energy. The core of such a massive star collapses to a neutron star or perhaps a black hole, while the outer layers are blown off the star in an explosive event that is known as a supernova.

In this thesis we discuss the evolution of stars that are less massive than about $10\,M_\odot$. When helium is exhausted in the core of such a low- or intermediate-mass star, it develops a degenerate carbon-oxygen core surrounded by a helium-burning shell which is in turn surrounded by the hydrogen-burning shell. These two burning shells come closer to one another while they move out and when they come very close, so-called thermal pulses occur. Meanwhile, the star has expanded again, onto the asymptotic giant branch (AGB). These large stars experience Mira pulsations, which typically have periods on the order of a year. At the moment of maximum radius during such a pulsation, the surface temperature of the star drops sufficiently to allow the formation of dust. If the dust couples to the gas, the high radiation pressure will cause the star to rapidly lose its envelope. The star loses enough mass that a supernova is prevented and ends its life as a white dwarf consisting of carbon and oxygen or, for the more massive stars, oxygen and neon. The former envelope of the star is visible for some time as a planetary nebula surrounding the proto-white dwarf, irradiated by the intense radiation of the hot central star. The white dwarf no longer produces energy, save for a possible thermonuclear shell flash when the white dwarf is still young, but cools and becomes less luminous. The cooling rate is determined by the mass of the white dwarf, the thickness of the hydrogen layer on its surface and the occurrence of shell flashes. A computer model for a star of $1\,M_\odot$ is shown in Fig. 1.1.

1.2 Binary-star evolution

Of the about 5000 stars that we can see with the naked eye, about 2000 are actually binary or multiple-star systems and it is thought that this fraction is representative for the stars in our Galaxy. The star closest to our Sun, Proxima Centauri, is a member of a triple system and it seems reasonable to assume that more than half of all stars are in a binary or multiple system.

Stars in a binary evolve in a potential that is determined by the gravity of the stars and the orbital motion in the binary. The surface that defines the sphere of influence within which a particle is bound to one of the two stars in the frame corotating with the binary is called the Roche equipotential surface and the two droplet-shaped spaces it confines are called the Roche lobes of the two stars. The point where the two Roche lobes touch is called the first Lagrangian point.

Stars in a binary with an orbital period in excess of 10 yr are likely to spend their lives

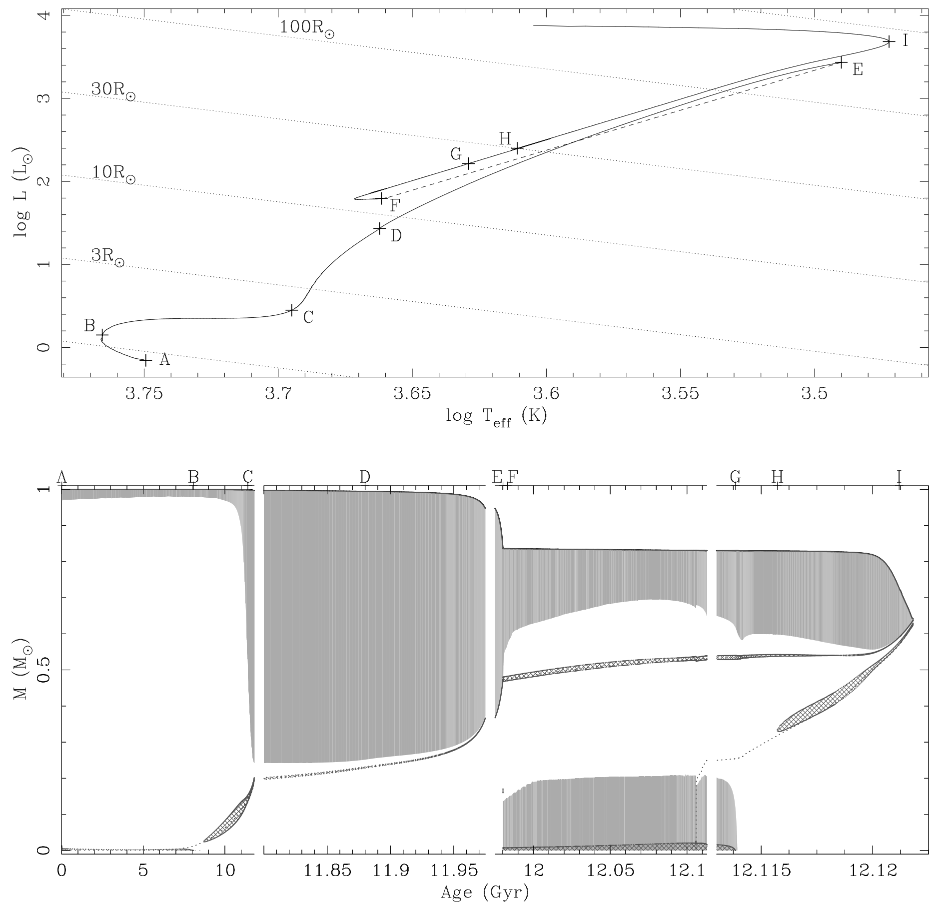

Figure 1.1: A computer model for the evolution of a star of 1 $M_\odot$ with wind mass loss, calculated with the evolution code of P. Eggleton. *Upper panel* (**a**): A Hertzsprung-Russell diagram for the model. The dashed line is where the helium flash occurs; the code replaces the pre-helium-flash model (E) with a post-helium-flash model (F). The dotted lines are lines of constant radius. *Lower panel* (**b**): A Kippenhahn diagram that shows the internal structure of the star as a function of time. Grey areas are convective regions, in hatched areas intense nuclear burning takes place. The thick line is the total mass of the star, the dotted lines are the masses of the helium and carbon-oxygen cores and often coincide with the burning shells. Notice the changes in scale of the time axis. The labelled points are A: zero-age main sequence, B: terminal-age main sequence, C: base of the giant branch, D: first dredge-up, E: helium flash, F–G: core helium burning phase, H: early asymptotic giant branch, and I: point where the hydrogen envelope has been blown away and the star starts contracting.

effectively as single stars, well inside their Roche lobes. In closer binaries, at least one of the stars may expand up to the size of its Roche lobe, for instance if the star becomes a giant. If this happens, gas from the giant can funnel through the first Lagrangian point into the Roche lobe of its companion, which may or may not accrete it. Thus, in a close-enough binary, mass can be transferred from one star to the other and in a later stage of evolution the reverse process may take place. Since the mass of a star is the dominant factor that determines the evolution of the star, mass transfer between stars can change the evolution of the two stars in a binary appreciably. A star of 1 $M_{\odot}$ on the red-giant branch could lose its envelope prematurely due to mass transfer, so that an undermassive helium white dwarf is formed, rather than the more massive carbon-oxygen white dwarf that would be the end product of such a star if it were single. In addition, the orbital period of the binary usually changes during mass transfer, because the transferred matter carries angular momentum from the donor to the accretor.

If the companion of the donor star is large enough and the mass-transfer rate not too high, the transferred matter will be accreted by the companion. If the companion is very small compared to the orbit, like in the case of a neutron star, the matter carries too much angular momentum to be accreted directly. In this case the matter will form an accretion disc around the neutron star and if the mass-transfer rate is higher than the Eddington accretion limit, some or most of the matter could be driven out of the system rather than accreted by the compact object. The gas in the accretion disc is heated and emits copious X-rays. Such systems, with a neutron star or black hole as accretor, are observed as X-ray binaries.

In the solar neighbourhood, the average distance between stars is rather high ($\sim$ 1 pc) so that it is unlikely that a binary interacts with other stars. It is therefore reasonable to assume that binaries in the galactic disc are primordial binaries. However, this is not true for dense stellar environments, like the galactic centre and globular clusters. The stellar density in the core of a globular cluster can be on the order of one million times higher than in the solar neighbourhood and hence the probability that an interaction between stars or between a star and a binary occurs is about 10^{12} times larger in the core of a dense globular cluster than in the solar neighbourhood. The fact that many luminous X-ray binaries are observed in globular clusters can probably be explained by this high density, for instance if these binaries are formed by the collision of a neutron star and a (sub)giant star (see Sect. 1.3.1).

1.3 Summary of this thesis

In this thesis we study the formation and evolution of compact binaries. Chapter 2 and 3 deal with the formation of luminous, ultra-compact X-ray binaries in globular clusters and rule out one of the proposed formation scenarios for these systems. In Chapter 4 we look in detail at observations of one particular X-ray binary in the galactic disc that is believed to be ultra-compact. Based on the observation of a long X-ray burst and a high neon-to-oxygen ratio in the X-ray spectrum, we show that the donor of this binary is probably the remnant of a helium white dwarf that was produced by a star no more massive than about 2.25 $M_{\odot}$. In Chapter 5 we discuss the formation of double white dwarfs. We present models that

Cluster	Position	P_{orb}	Indirect indication		
			low f_{opt}/f_x	burst max.	spectrum
NGC 1851	0512–40	?	U	U	U
Terzan 2	1724–31	?	—	U	N
Liller 1	1730–33	?	—	—	—
Terzan 1	1732–30	?	—	—	—
NGC 6440	1745–20	?	—	—	N
Terzan 5	1745–25	?	—	—	U
NGC 6441	1746–37	5.7 hr	—	N	N
Terzan 6	1751–31	12.4 hr	—	—	N
NGC 6624	1820–30	11.4 min	U	U	U
NGC 6652	1836–33	?	U	U	U
NGC 6712	1850–09	20.6 min	U	U	U
NGC 7078	2127+12a	22.6 min	—	U	—
NGC 7078	2127+12b	17.1 hr	—	—	—

Table 1.1: Luminous X-ray binaries in the galactic globular clusters. The columns list the name of the cluster, the position of the source, the orbital period and three indications for an ultra-short (U) or normal (N) period, based on the optical to X-ray luminosity ratio, the maximum luminosity in bursts and the X-ray spectrum. See the main text for more explanation. Adapted from Verbunt & Lewin (2004).

describe the evolution of a binary through two mass-transfer phases in which the two white dwarfs are formed. We conclude that we can explain the observed masses and periods well, but that it is more difficult to find a model that also explains the observed age difference of the two components.

1.3.1 The formation of luminous X-ray binaries in globular clusters

(Chapter 2 and 3)

Thirteen luminous X-ray sources are detected in the globular clusters of our Galaxy (Verbunt & Lewin 2004; Verbunt 2005). All of these sources are low-mass X-ray binaries in which a low-mass star transfers mass to a compact object. Twelve of these systems are X-ray bursters and hence the compact object must be a neutron star, for the 13th source this is not certain. For 6 of these 13 systems the orbital period is measured and 3 out of these 6 have an ultra-short ($\lesssim 40$ min) period. These systems are 4U 1820–30 in NGC 6624 which has an 11.4 min period (Stella et al. 1987), 4U 1850–087 in NGC 6712 with a 20.6 min period (Homer et al. 1996) and recently a 22.6 min orbital period was found for M15 X-2 (in M 15/NGC 7078) (Dieball et al. 2005) (see Table 1.1).

The other 7 X-ray sources have no detected orbital periods. However, indirect methods are available that give an indication as to whether an X-ray binary is ultra-compact or not.

The first method uses the fact that most optical light from luminous low-mass X-ray binaries comes from re-processing of X-rays in the accretion disc. A short orbital period means a small disc and hence a relatively low optical luminosity with respect to the X-ray luminosity (Van Paradijs & McClintock 1994). The second method was found by Kuulkers et al. (2003) and is based on the peak luminosity reached during X-ray bursts. This maximum luminosity is compatible with the Eddington luminosity for hydrogen-poor material for two systems with measured ultra-short periods, whereas it is compatible with the Eddington luminosity for hydrogen-rich material for a source with a normal period. The third method comes from a simple two-component model to explain the X-ray spectra of these systems by Sidoli et al. (2001). This model gives realistic and self-consistent solutions for three systems believed to be ultra-compact, and non-consistent solutions with unrealistic parameters for sources with normal periods. For more details on these methods, see Verbunt & Lewin (2004); Verbunt (2005). The last three columns of Table 1.1 show for each of the luminous X-ray sources in the globular clusters whether they are ultra-compact (U) or normal (N) according to these indirect methods. From the Table one can infer that of the thirteen luminous X-ray sources in globular clusters, certainly 3, probably 5 and possibly 6–8 are ultra-compact binaries. This is in sharp contrast to the much-lower fraction of ultra-compact binaries in the field (Deutsch et al. 1996).

There are three explanations for the formation of ultra-compact X-ray binaries in globular clusters. The first formation scenario starts with a binary of a neutron star and a massive companion. If the companion becomes a giant its envelope can engulf the neutron star and cause a spiral-in. The core of the companion thus forms a close binary with the neutron star and the orbital period will become shorter due to gravitational radiation until mass transfer starts. If the companion had a helium core and the orbit after the spiral-in is very close, there may be no time to burn the helium so that helium is the main constituent of the transferred matter. If the star had a helium core and the orbit is wider, the core would become a helium star and convert most of its helium to carbon and oxygen. This would be similar to the case where the companion had a carbon-oxygen core at the time of the spiral-in. Although stars of sufficient mass for a spiral-in with a neutron star do no longer exist in the galactic globular clusters, it can take some time before gravitational radiation causes Roche-lobe overflow to occur so that this could explain the observed systems in the galactic disc and in globular clusters today. A second formation scenario is likely to happen only in dense stellar environments, such as (the cores of) globular clusters. In this scenario the neutron star collides with a (sub)giant star, the envelope is expelled and the neutron star forms a binary with the core of the giant (Verbunt 1987). Since the probability of such a collision is largest if the star is on the sub-giant branch, the companion to the neutron star is likely to be a helium white dwarf. It has recently been found that this scenario could provide for a sufficiently large formation rate to explain the observed numbers of luminous sources (Ivanova et al. 2005).

A third mechanism to explain the ultra-compact X-ray binaries starts with a neutron star and a main-sequence star that loses angular momentum due to strong magnetic braking. The angular-momentum is lost from the orbit due to spin-orbit coupling and causes the orbit to shrink. We call such a system converging. When the initial orbital period is short, the minimum period lies around 70 min (Paczynski & Sienkiewicz 1981). At this point the donor becomes degenerate and the orbit starts expanding again. If the initial period is long, a helium core develops and mass transfer becomes fast enough to overcome the effect of angular-momentum loss, so that the orbit expands until the donor has transferred all of its mantle and a low-mass helium white dwarf is formed (Webbink et al. 1983). Such a system diverges. For a narrow range of initial periods around the bifurcation period between converging and diverging systems the donor star fills its Roche lobe around the terminal-age main sequence. Such a star becomes degenerate at smaller radius due to the high helium abundance while a pure helium core is not yet formed. In this case, the period minimum can be much smaller than $\sim$ 70 min (Tutukov et al. 1985) and ultra-short orbital periods of 11 min can be reached (Podsiadlowski et al. 2002). We will refer to this mechanism as *magnetic capture*. Pylyser & Savonije (1988) investigated the magnetic-capture scenario and found no periods lower than about 38 minutes. They stopped their calculations at the Hubble time, while Podsiadlowski et al. (2002) only show the time that elapsed since mass transfer started.

The interesting feature about the magnetic-capture scenario is that for an X-ray binary with an orbital period of 11 min the period derivative can be either positive or negative, depending on whether the system has already passed the period minimum or not. A negative period derivative has been observed several times for the 11.4 min binary in NGC 6624 (Van der Klis et al. 1993b; Chou & Grindlay 2001) and this suggests that the binary evolved along the lines of the magnetic-capture scenario. However, the negative period derivative could be apparent due to acceleration of the binary in the cluster potential (Van der Klis et al. 1993a). Figure 1.2 shows that the acceleration at the projected distance of the binary from the centre of the cluster seems insufficient to explain the observed period derivative, especially if the gravitational acceleration should be twice as strong in case the intrinsic $\dot{P}$ is positive. However, observations with HST of the optical counterpart of the X-ray binary place it six times closer to the cluster centre (King et al. 1993), which makes it again more probable that the negative period derivative is due to acceleration.

We investigate the magnetic-capture scenario in Chapter 2 and 3. In Chapter 2 we investigate the magnetic-capture scenario along the lines of Podsiadlowski et al. (2002), using the magnetic-braking law by Verbunt & Zwaan (1981) and assuming that half of the transferred mass is lost from the system. In addition we do not allow evolution beyond the Hubble time. We calculate models starting with a binary that consists of a neutron star and a low-mass ($0.7\,M_\odot \leq M_\mathrm{i} \leq 1.5\,M_\odot$) zero-age main-sequence star. We vary the initial mass of the donor, the initial period and the metallicity of the stars and produce several grids of models. We use these grids and interpolate between two adjacent models to derive an evolutionary scenario for a binary with an arbitrary initial period. This way we calculate the distribution of a simulated population of one million stars with an age between 10 and 13 Gyr for each initial donor mass in our grid. Next we add these distributions to produce a period distribution for a population of 10 million of these stars at the age of the globular clusters. The distribution for $Z = 0.01$ thus obtained shows us that one in 10^7 binaries that evolved this way should have an orbital period of 11 min and that for each such system there should be about 100 binaries with an orbital period $\lesssim 20$ min. We conclude that the initial period of a binary must be very close to the bifurcation period in order for it to evolve to an ultra-compact system. Furthermore, such a system evolves very rapidly through the period minimum, so that there is only a small probability to observe it in the ultra-compact regime. We also find that there is no contribution from the most massive donors in our grid ($\geq 1.2\,M_\odot$) to the ultra-compact binaries.

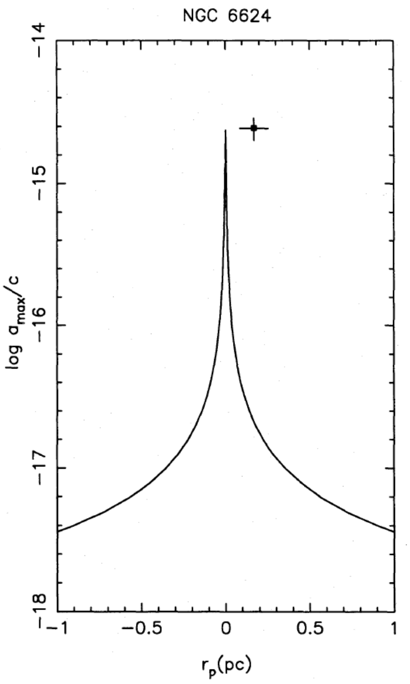

Figure 1.2: The maximum acceleration along the line of sight $a_{\max}$ as a function of the projected distance from the cluster centre, according to a cluster model for NGC 6624 (curve) compared to the measured position and acceleration of the 11.4 min binary (dot with error bars). In more recent observations the binary is closer to the centre (King et al. 1993). Taken from Van der Klis et al. (1993a).

In Chapter 3 we expand these grids of models by varying more parameters. We reduce the strength of the magnetic-braking law that we used in Chapter 2 and in addition we use a more modern law, based on the measured ranges in rotational velocities of stars in the Hyades and Pleiades and including saturation of the angular-momentum loss at a certain critical rotation velocity (Sills et al. 2000). We show that our results from Chapter 2 depend strongly on the magnetic-braking law we used. If we reduce the strength of magnetic braking by simply scaling down this law with a factor of 4, the shortest orbital period found in our models increases from about 10 min to 23 min. This is due to the fact that since magnetic braking is weaker, the systems need more time to reach the ultra-compact regime. Thus many systems may only reach this regime after the Hubble time, so that they do not contribute to the simulated population at 10 to 13 Gyr. Secondly, because the evolution needs more time, a small offset in initial period has larger consequences for the evolution than before. This basically means that the range of initial periods that lead to ultra-compact binaries is even narrower than before. If there is no magnetic braking at all, or if we use the saturated magnetic-braking law by Sills et al. (2000), the shortest periods found lie around 70 min. Reducing the strength of the magnetic braking used in our models to perhaps more realistic values thus changes the probability of forming an ultra-compact X-ray binary with the magnetic-capture scenario from very improbable to impossible.

The conclusions of these two chapters have important consequences for our understanding of the formation of the observed low-mass X-ray binaries; they cannot have been formed by the magnetic-capture scenario. Interestingly, this could be confirmed observationally, as we mention in Chapter 3. Our models for magnetic capture predict that donors in an ultra-compact binary with a negative period derivative still have hydrogen on their surface and this surface hydrogen vanishes around the period minimum. Thus, if hydrogen were observed in the 11.4 min binary this would prove that the orbit is shrinking, whereas conclusive evidence of the lack of hydrogen at the surface would suggest that the intrinsic period derivative is positive. Furthermore, if in such a study carbon and oxygen would be found abundantly, this would suggest that the binary was formed long ago in a spiral-in caused by a massive star and the white dwarf was brought to Roche-lobe overflow by gravitational radiation only recently. Most probably, helium will be the most abundant element which would allow both the the spiral-in scenario and the collision-scenario to explain the formation of this binary.

1.3.2 The presumed ultra-compact X-ray binary 2S 0918–549

(Chapter 4)

The object 2S 0918–549 is an X-ray binary with a low optical to X-ray flux ratio (Chevalier & Ilovaisky 1987). As shown by Van Paradijs & McClintock (1994), this is an indication that the system might be an ultra-compact binary with an orbital period less than 1 hr. The object also has an unusually high neon-to-oxygen abundance ratio. Juett et al. (2001) show that of a set of 56 low-mass X-ray binaries, there are four sources that display this phenomenon. Two of these four systems have measured ultra-short periods of 18 min (in 4U 1543–624, see Wang & Chakrabarty 2004) and 21 min (in 4U 1850–087, see Homer et al. 1996). This observation therefore provides an extra indication that 2S 0918–549 is an ultra-compact binary. Because such a binary cannot be formed by stable mass transfer (Chapter 2 and 3) and a collision between a neutron star and a (sub)giant is rather improbable in the galactic disc, 2S 0918–549 probably formed from a spiral-in following dynamically unstable mass transfer by the companion to the neutron star and leaving the core of that companion exposed.

Optical spectroscopy of 2S 0918–549 shows a lack of spectral lines from hydrogen and helium (Nelemans et al. 2004). This suggests that the donor is a carbon-oxygen or neon-magnesium-oxygen white dwarf. However, like two other LMXBs identified by Juett et al. (2001), this system shows type-I X-ray bursts caused by thermonuclear shell flashes on neutron stars (see Sect. 4.1). Such bursts, of duration 10 s to several minutes, can only be explained by the presence of helium, possibly in combination with hydrogen (Juett & Chakrabarty 2003; Nelemans et al. 2004) and the duration of the burst is proportional with the hydrogen content. 2S 0918–549 experienced a burst that lasted almost 40 min (see Sect. 4.3) which would suggest a high hydrogen content, in blatant contradiction to the optical spectrum and the presumed ultra-compact nature of the binary.

Because 2S 0918–549 is a persistent source with a low accretion rate ($\sim 1\%$ of the Eddington accretion limit, see Jonker et al. 2001) we argue that pure helium has been accreted slowly but for a long time by the neutron star. Thus, a thick layer of helium has accumulated on the surface of the neutron star, which explains the long duration of the burst. The donor could therefore be a helium white dwarf, although it is not clear why lines of helium should be missing from the spectrum. My contribution to this chapter is mainly in Sect. 4.5.2, where we present a number of progenitor models for the donor of 2S 0918–549. We assumed that the star that is now the donor in 2S 0918–549 was the core of its progenitor and exposed after a spiral-in. First we argue that the donor cannot be a massive carbon-oxygen white dwarf or a neon-magnesium-oxygen white dwarf. Such stars have masses that are higher than about 0.4–0.5$M_{\odot}$, which is thought to be the upper limit to the mass of a white dwarf that can have stable mass transfer. Thus, any white-dwarf donor with stable mass transfer should be either a helium white dwarf or a low-mass carbon-oxygen white dwarf, once the core of a giant star. We therefore consider the cores of our model stars that evolve from the zero-age main sequence (ZAMS), via the red giant branch (RGB) to the asymptotic giant branch (AGB).

Stars of 1 $M_{\odot}$ or more on the RGB have a helium core that was formed by hydrogen fusion at least in part via the CNO cycle. In this process the neon abundance does not change, but the oxygen abundance drops because oxygen is converted to nitrogen in the CNO cycle. Thus the neon-to-oxygen abundance ratio in a helium core is higher than it was at the ZAMS. The precise number depends on the temperature at which the burning takes place and thus, among others, on the mass of the star. In our stellar models this ratio increases to about twice the ZAMS ratio for a star of 1 $M_{\odot}$ and to almost 20 times the ZAMS ratio for a 5 $M_{\odot}$ star.

A star on the AGB has a carbon-oxygen core, the 'ashes' of helium burning. In a side reaction to the helium-burning process some nitrogen is converted into neon-22, but this happens on a much smaller scale than the production of oxygen. The oxygen abundance therefore rises much more than the neon abundance and the models show a neon-to-oxygen ratio that is much lower than it was initially: 13–16% of the ZAMS value. We conclude that the donor of 2S 0918–549 that we observe today is probably the central part of a helium-white dwarf, the former core of a progenitor no more massive than about 2.25 $M_{\odot}$. This is compatible with the observations of long X-ray bursts and the high neon-to-oxygen abundance ratio, although it is unclear why helium lines are lacking in the optical spectrum.

1.3.3 The formation of double white dwarfs

(Chapter 5)

Double white dwarfs, binaries in which both components are white dwarfs, are sought for systematically by the SPY (ESO SN Ia Progenitor surveY) project (*e.g.* Napiwotzki et al. 2001). If these systems have short enough orbital periods and a mass that exceeds the

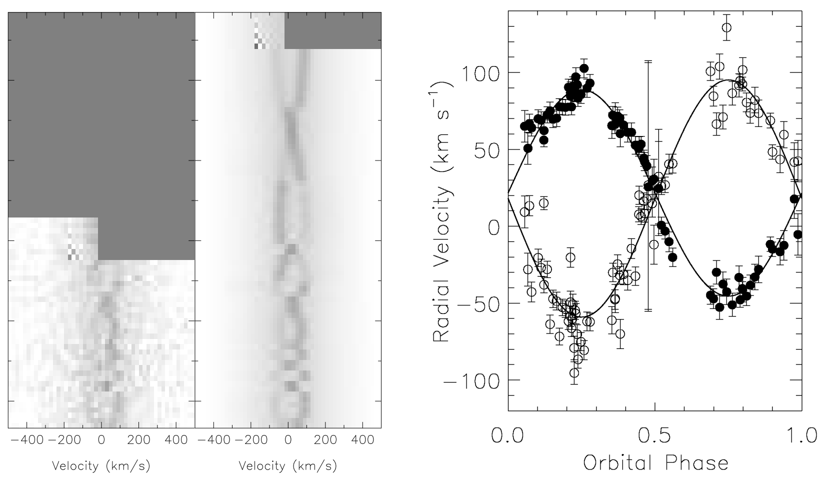

Figure 1.3: Observations of WD 0316+768. *Left panel:* Spectrograms (left-most) and the fit to these data. *Right panel:* Radial velocities measured for both components (symbols) and least-squares fits of sine functions to these points (solid curve). Adapted from Maxted et al. (2002b).

Chandrasekhar limit, they might produce supernovae of type Ia (Iben & Tutukov 1984). Furthermore, they may be the dominant source of low-frequency gravitational radiation (Evans et al. 1987; Hils et al. 1990). Ten double white dwarfs have been observed as double-lined spectroscopic binaries to date. These systems typically have orbital separations of a few solar radii or less and component masses between about 0.3 and 0.8 $M_{\odot}$ (see Table 6.1). Since these white dwarfs were once the cores of stars on the giant branch with radii of several tens to several hundreds of solar radii, a drastic orbital shrinkage must have taken place around the formation of the youngest white dwarf. It is usually assumed that the progenitor of this white dwarf filled its Roche lobe while it had a deep convective envelope, so that the ensuing mass transfer was dynamically unstable and the envelope of the donor engulfed the white dwarf that was already formed. The two compact objects would then spiral inwards due to drag forces inside this common envelope, while the orbital energy that is liberated is used to expell the envelope from the system (Webbink 1984).

In Chapter 5 we try to find an evolutionary scenario for these 10 observed systems. We follow the lines of Nelemans et al. (2000) who did very similar work, but based on 3 observed systems rather than 10 and with use of many analytical approximations where we use a stellar evolution code for more detailed calculations. Among the advantages of the use of an evolution code is that we can calculate for a set of progenitor models the radius of the star and the binding energy of its envelope at every moment of its evolution. This enables us to calculate the efficiency parameter for a common envelope with spiral-in $\alpha_{\rm ce}$. Another difference is that we consider more-massive progenitors and stars on the asymptotic giant branch as possible progenitors.

We confirm the conclusion of Nelemans et al. (2000) that the formation of the observed systems cannot be explained by the scenario where the first white dwarf is formed after conservative mass transfer and the second white dwarf in a common envelope with spiral-in, or by the scenario in which two occurrences of such a spiral-in take place. A different mechanism in which a donor star can lose its envelope is therefore required and we again follow Nelemans et al. (2000) in their prescription of envelope ejection with angular-momentum balance, rather than energy balance. This prescription uses an efficiency factor γ to relate the angular momentum that is carried by the ejected envelope to the average angular momentum of the progenitor system. This prescription was also used for this purpose by Nelemans & Tout (2005), but again with approximations for the stellar parameters. We share their conclusion that all observed masses and orbital periods can be explained with this mechanism, if $1.5 \leq \gamma \leq 1.75$. However, this would imply that the envelope matter somehow gains extra angular momentum from the binary before it is lost and at this moment there is no physical explanation for this.

We therefore introduce two slightly different prescriptions for the scenario of envelope ejection with angular-momentum balance. In the first prescription it is assumed that the matter is transferred from the donor to the companion and then re-emitted isotropically. The second prescription is for an isotropic wind from the donor star. These two prescriptions can explain the masses and periods of all observed systems, but now with an efficiency parameter $0.9 \leq \gamma \leq 1.1$. These prescriptions therefore need no additional physical explanation for the high angular-momentum losses. The observed masses and periods can be explained with either an envelope ejection with a γ-prescription followed by a spiral-in with the α-prescription, or with two subsequent γ-envelope ejections. However, if we want our models to explain in addition the difference in cooling age between the two components of a binary, found by the observers by comparing their observations to white-dwarf cooling models, we find that this is more problematic. Some systems can still be explained with the same values for γ, while for others we must allow values that are much farther form the desired values than before. We list the best solutions in Table 6.5 and one of them is schematically displayed in Fig. 1.4.

Among the solutions that can explain the observed double white dwarfs there is one that could explain the observation that the oldest white dwarf in the system PG 1115+116 is a DB white dwarf, *i.e.* has no hydrogen in the spectrum (Maxted et al. 2002a). The scenarios for stable mass transfer or envelope ejection predict that there is a thin layer of hydrogen at the surface of a white dwarf produced this way so that it should be a DA white dwarf, *i.e.* with hydrogen in its spectrum. Maxted et al. (2002a) suggest that the star may have experienced a giant phase after the first mass-transfer phase. This scenario corresponds to solution 54 in Table 6.5, in which the 0.89 $M_{\odot}$ helium core of a 5.42 $M_{\odot}$ progenitor is exposed due to envelope ejection with the γ-prescription. Such an exposed core becomes a helium star and massive helium stars can become giants. Most of the mass in such a giant is in the carbon-oxygen core and it is possible that this star loses its outer layers, either by Roche-lobe overflow or by a stellar wind, without much change to the total mass and the

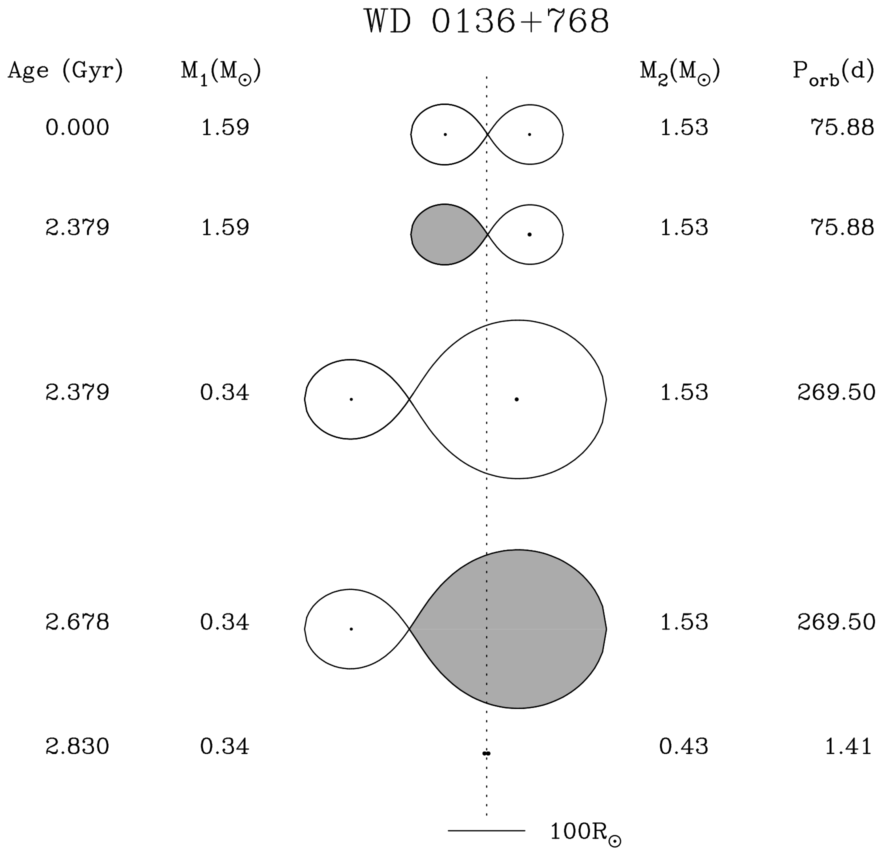

Figure 1.4: Schematic representation of the evolution of an initial binary that leads to the double white dwarf WD 0136+768 with the observed masses, orbital period and age difference. This scenario corresponds to solution 22 in Table 6.5, in which the primary ejects its envelope with $\gamma \approx 0.95$ (from panel 2 to 3 in the Figure) and the secondary causes a spiral-in with $\alpha_{\rm ce} \approx 1.00$ (panel 4 to 5). The Figure shows the stars and their Roche lobes with respect to the centre of mass of the binary (dotted vertical line). The numbers are the age since the zero-age main sequence, the two masses and the orbital period. The components of the double white dwarf that is formed in this scenario have an age difference of 299 Myr; compare the observed age difference of 450 Myr according to the cooling models. The final panel shows the binary at its current age, according to the cooling age for the youngest white dwarf. The final orbital separation is less than 5 $R_\odot$ and hardly visible.

orbital period. It is interesting that such an evolutionary scenario is indeed amongst our solutions.