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Introduction and Summary

Since most stars are members of binary or multiple stellar systems (50%-100%; Abt, 1983), the study of binary systems is an important topic in astronomy. Many different types of stars are gravitationally bound in nature, and a great diversity of astrophysical phenomena result from interactions between binary components.

One group of interacting binaries of great interest is that of the low-mass close binary systems with a compact component. Such systems consist of a low-mass (i.e. $M_* < 2.3\ M_\odot$) mostly hydrogen-burning star accompanied by a white dwarf, a neutron star or possibly a black hole. When the low-mass (mostly hydrogen-burning) star tranfers mass towards its compact companion, phenomena such as nova-outbursts, strong emission of X- (and possibly Gamma-) radiation, periodic and quasi-periodic optical and/or X-ray oscillations and even supernova-explosions may be observed as a result of the deposition of matter onto the compact component.

Although some 170 low-mass interacting close binaries containing a compact object have been observed (Ritter, 1987), the formation of these systems is still poorly understood and probably a very rare phenomenon. Nevertheless, it is clear that the compact component is the remnant of the originally most massive star of the system, the so-called original primary. Furthermore, the generally very short orbital periods of these low-mass close binaries strongly indicates that extensive loss of orbital angular momentum (and mass) must have taken place in the formation-stage of the system (Eggleton, 1986).

A very efficient process of extraction of angular momentum from a binary system is friction while it is imbedded in a common envelope. Such a situation may ensue when the expanding primary has become a giant star and starts transferring mass towards its (much) less massive companion. Since mass transfer occurs from the more massive star towards the less massive star, the process of mass transfer is unstable and very rapidly the binary separation decreases. Soon, the giant's envelope engulfs the low-mass companion and forms a common envelope around both the nuclearly processed core of the giant and the low-mass companion. The latter process is accompanied by strong mass loss from the system

through the outer Lagrangian points, if the mass ratio of the progenitor system is < 0.3 to 0.4 (Packet, 1988). Detailed studies of common-envelope evolution are beyond the scope of this project and none of the attempts made so far have been able to predict the outcome of such a phase with any degree of credibility (de Kool, 1987). Nevertheless, one can demonstrate (see e.g. Webbink, 1984) that the final system has a relatively small orbit and consists of the original secondary, accompanied by the compact core of the original primary. The envelope of the primary, which formed the common envelope has thereby been removed from the system.

Depending on the orbital period of the low-mass close binary system after the common-envelope phase, the subsequent evolution of the system is determined by either the nuclear evolution of the low-mass hydrogen burning star (i.e. the secondary), which causes a slow expansion of this star, or by orbital angular-momentum loss (AML) from the system, which leads to a decrease of the orbital period. Both processes decrease the separation between the surface of the secondary star and its surrounding Roche-lobe and inevitably, a new mass-transfer phase will ensue. If stellar expansion occurs more rapidly than the contraction of the Roche-lobe due to orbital angular-momentum losses, i.e. if the evolutionary timescale of the secondary, τ_{ev}, is shorter than the timescale for angular momentum loss, τ_{AML}, the mass-transfer phase is likely to be governed by the expansion of the secondary star and will lead to an increasing orbital separation of the binary. Alternatively, if τ_{AML} is less than τ_{ev}, the mass-transfer phase is determined by the orbital angular momentum losses and the binary period will decrease secularly. In this work, these two types of binary systems will be referred to as <u>diverging</u> and <u>converging</u> systems, respectively.

Part of this work is devoted to a study of the combined effects of the secondary's nuclear evolution and the orbital angular momentum losses on the evolution of these low-mass close binary systems. We will introduce a critical initial orbital period P_{bif}, which separates the systems with initial orbital period $P_i > P_{bif}$, and those with $P_i < P_{bif}$, and which evolve as diverging and converging systems, respectively.

Various mechanisms for orbital angular momentum loss in low-mass close binary systems have been proposed. The process of gravitational radiation, in which gravitational waves are emitted from the system at the expense of the orbital energy (Landau and Lifschitz, 1959) occurs in all binary systems, but becomes an effective mechanism for angular momentum removal only in close binary systems for which the orbital period does not exceed a few hours (Paczynski, 1967; Taam et al., 1980; and references therein). Although the process of gravitational radiation is very effective and even dominant in some specific evolutionary phases of very close low-mass binaries, it has been shown to be insufficient to explain the observed mass-transfer rates in cataclysmic variable binaries and low-mass X-ray binaries with orbital periods of a few hours to about half a day (Patterson, 1984).

The existence of a second, more efficient mechanism for orbital angular momentum removal can be inferred from the rotational characteristics of single low-mass main-sequence stars that have a convective envelope. Observations show that the rotation of such stars is braked on a relatively short timescale of order 10^7 to 10^8 yrs (Skumanich, 1972; and references therein).

In a close binary, such braking will also occur but tidal forces will continuously attempt to spin up the braked star, to restore co-rotation with the orbital motion (Huang, 1966). As a result, orbital angular momentum will continuously be fed into the rotation of the main-sequence component and then be lost by means of the rotational braking mechanism (Verbunt and Zwaan, 1981).

In order to understand the evolution of low-mass close binaries, it is essential to study the mechanism of rotational braking by means of a magnetically coupled stellar wind of single low-mass stars and derive the physical parameters which determine this process.

For this reason, part of this work is also devoted to the study of the evolution of single low-mass stars, with rotational braking.

This work can be divided into the following three main parts:

1) Studies of the evolution of single low-mass stars with rotational braking (Section I.1).

2) Studies of the evolution of low-mass close binaries with a compact component in which mass transfer is driven by interior evolution and angular momentum losses (Section I.2).

3) Studies of the spin evolution of magnetized neutron stars in low-mass close binaries with a special aim to understand the origin of the millisecond pulsars in binaries (Chapter II). In this Chapter, the computational results obtained in Section I.2 are applied to observed systems, in order to understand the rotational status of the neutron star in these systems.

We now briefly summarize the contents of each of these three parts of this work.

1. The internal and rotational evolution of single low-mass stars (section I.1).

Since the original suggestion by Schatzmann (1962), enhanced magnetic activity (and hence stellar rotational braking) has been shown to be present in all main-sequence stars with color-index B-V > 0.4, in subgiants with 0.4 < B-V < 0.6 and giants with B-V > 0.6 (Rutten, 1986, 1987). Direct comparison of these observational properties with the evolution of the internal structure of low-mass single main-sequence stars, subgiants and giants indicates that the extent of the convective envelope can, in a first approximation, be used as a single parameter for the occurrence of magnetic braking (Pylyser and Savonije, 1988a).

Main-sequence stars with mass $M_* > 1.25\ M_\odot$ do not have convective envelopes sufficiently extended to yield magnetic braking. However, in the course of their evolution towards the giant stage, the convective envelope grows towards the center of the star and rapidly exceeds the minimum extent necessary to sustain magnetic braking.

A study of the evolution of the rotation rates of subgiants (Rutten and Pylyser, 1988) indicates that the observationally derived rotation-rate/age relation derived for G-type main-sequence stars (Skumanich, 1972; Smith, 1979; Soderblom, 1983), also approximately describes the evolution of sub-giant rotation rates. Indeed, reconstruction of the

distribution of rotational velocities of low-mass subgiants and giants only in terms of changes in the moments of inertia during stellar evolution, was successfull for giants, but necessitated the inclusion of the process of magnetic braking in the case of subgiants.

2. The evolution of low-mass close binaries (Section I.2).

a. Model computations.

The above obtained results on the rotational evolution of single low-mass stars allow for an extension of low-mass binary calculations towards higher initial masses and more evolved initial states of the secondary component.

So far, such calculations included gravitational radiation (Paczynski, 1967; Faulkner, 1971; Taam et al., 1980; and references therein), and if magnetic braking was included, the initial mass of the hydrogen-burning component was chosen to be less than about 1.25 $M_\odot$ (Taam, 1983; Iben and Tutukov,1984), since more massive stars have B-V < 0.4, and were thought not to have magnetic braking.

In the present study, the mass-losing component is assumed to be more massive (up to 2.0 $M_\odot$). Such stars normally do not have extended convective envelopes until they become (sub)giants and are therefore not expected to be subject to magnetic braking. However, during the phase of mass-transfer, we follow the evolution of the extent of the convective envelope of the secondary and whenever the critical extent is exceeded, magnetic braking according to the description of Verbunt and Zwaan (1981) is included in the binary calculations.

The numerical calculations performed in Chapter I indicate that the bifurcation period varies between about 0.5 and 0.7 days, depending on the initial masses of both components. For a given mass of the compact star, the bifurcation period is only a function of the mass of the donor star, but for each value of the stellar mass of the donorstar, it corresponds to a different initial evolutionary state of this star. For example, in the case that the secondary star is initially a 1.0 $M_\odot$-star, it may have developed a small helium core at the onset of mass transfer

and subsequently still form a converging binary system, while an initially 2.0 $M_\odot$ donor star should not have evolved to a core-hydrogen abundance $X_c < 0.30$, in order to evolve as a converging system.

If the extent of the convective envelope exceeds its critical value, the evolution of a converging system and the mass-transfer rate between both components of such a system is at first governed by the process of magnetic braking. This situation lasts until either the orbital period of the system has become so short that the process of angular momentum loss, due to gravitational radiation becomes dominant, or the support of the magnetic field, i.e. the underlying radiative layer (Parker, 1955), disappears when the secondary becomes fully convective (Robinson et al., 1981; Spruit and Ritter, 1983; Rappaport et al., 1983). From then on, the evolution of the converging system is determined by gravitational radiation only.

If the star is on the Zero Age Main-sequence (ZAMS) when it becomes fully convective, the calculations show that it has a mass of about 0.3 $M_\odot$ when rotational braking stops, and that the star briefly detaches from its Roche-lobe. Although it is often argued that the subsequent detached phase corresponds with the observed period gap of cataclysmic variables between 3 and 2 hours, the calculations show that the scenarios provided so far in order to model the period gap are either insufficient or incorrect, since they fail to reproduce the observed extent of the period gap. Furthermore, in converging systems in which the mass-losing component is not a ZAMS star, the secondary does not become fully convective at the observed upper limit of the period gap, but at a lesser value of the orbital period, and the subsequent detached phase is systematically shorter and less evident in case of more evolved secondary stars.

Despite the above failures in modelling the period gap in detail, the evolutionary results for converging binaries with $P_{orb} > 3$ hours, for which magnetic braking is believed to determine the mass-transfer rate and govern the evolution of the binary, provide theoretical characteristics that are qualitatively in good agreement with the observed ones. The calculations indicate that the presence of secondary stars with different evolutionary states in the sample of observed systems may contribute to the observed large spread in $\dot{M}$ as a function

of the orbital period P_{orb}. The upper bound of the observed distribution of systems in the $\dot{M}/P_{orb}$ plane is then produced by the presence of systems with Zero Age Main-Sequence donor stars while the lower bound is produced by systems with more evolved donor stars, which probably had an initial period P_i close to (but shorter than) the corresponding bifurcation period P_{bif}. An explanation is presented why the process of magnetic braking is of essential importance to explain these observed characteristics (Pylyser and Savonije, 1988b).

Gravitational radiation becomes dominant when the orbital period of the system becomes shorter than about 2 hours, even if it is assumed that the process of magnetic braking is still present. Whenever the decreasing timescale of gravitational radiation becomes comparable to the increasing thermal timescale of the continuously mass-spilling secondary star, the donor star departs from thermal equilibrium. Independently, nuclear burning in the core of the star fades and the star becomes degenerate, which causes it to subsequently expand as reaction to mass loss. As a result, the binary period begins to increase and the strong departure from equilibrium terminates. It has been shown that the minimum orbital period attained is about 80 minutes, if the donor star has a core-hydrogen abundance $X_c \approx 0.7$, and about 40 minutes, if $X_c \approx 0.00$ (Paczynski, 1981; Rappaport et al., 1983; Paczynski and Sienkiewicz, 1981).

Binary systems starting mass-transfer with $P_i > P_{bif}$ contain secondary stars which are relatively evolved (i.e. $X_c < 0.33$ for a 2.0 $M_\odot$-star and $X_c < 0.07$ for a 1.5 $M_\odot$-star; see Pylyser and Savonije, 1988a). These stars will develop a helium core during the mass-transfer phase. Such binary systems can then be observed as wide cataclysmic variables if the compact component is a white dwarf or as bright low-mass X-ray binaries, if it is a neutron star (Webbink et al., 1983). Although binary systems with P_i close to P_{bif} are still subject to significant angular momentum loss due to magnetic braking, the importance of magnetic braking during the mass-transfer phase decreases with increasing initial period P_i and may be regarded as almost insignificant for $P_i > 1.3$ days.

When due to mass transfer, the hydrogen-rich envelope of the secondary has been exhausted, the remnant helium core shrinks within its

Roche-lobe and mass transfer terminates. If the compact component in the system is a neutron star, it stops accreting and starts radiating away its rotational energy, due to magnetic dipole radiation. The system can then be observed as a binary radio pulsar (Paczynski, 1983; Savonije, 1983; Rappaport and Joss, 1983). This subject is considered in Chapter II (see below).

b. Applications to observed systems.

As an application of both the semi-analytical and the numerical descriptions of the evolution of low-mass close interacting binary systems, we examine and discuss in section I.2 the evolution and current status of some observed systems. In summary, the results are as follows.

(i) The binary system A0620-00 is a transient X-ray source with a possible recurrence-time of about 70 years. The orbital period is 7.75 hours, the spectral type of the secondary is K5V and more interesting, the compact component is the best binary black-hole candidate known at present, its mass being > 3.2 $M_\odot$ (McClintock and Remillard, 1986). In a first approximation, the evolution of the system was approached semi-analytically (de Kool et al., 1986). These authors found that the primordial system consisted of a 40 $M_\odot$ star and a 1.0 $M_\odot$ companion with an orbital period of about 500 days. Assuming that the system survived the common-envelope phase and the supernova-explosion of the massive component and that during the subsequent and presently observed phase, the mass transfer is driven by gravitational radiation only, limits on some binary parameters could be obtained. They found that the initial secondary and primary mass were < 2.0 $M_\odot$ and between 27 to 46 $M_\odot$, respectively.

In a second refined investigation, some of these limits were re-examined with the use of numerical calculations, including angular momentum losses due to magnetic braking (Pylyser and Savonije, 1988a). It was found that the presently observed secondary has a mass of about 0.43 $M_\odot$ and can have developed a small He-core of about 0.01 $M_\odot$, even before mass transfer started. The initial mass of the secondary must have been between 1.0 to 1.5 $M_\odot$ and the latest mass-transfer phase

started when the system had an orbital period of about 0.55 days.

(ii) A discussion is given on the evolution of the low-mass binary radio pulsar PSR 1831-00, which, according to Dewey et al. (1986), has a white dwarf secondary component with a mass of 0.06 to 0.13 $M_\odot$ and an orbital period of 1.8 days. We find that the mass of the white dwarf could be somewhat higher, i.e. 0.17 to 0.20 $M_\odot$. Mass transfer must have started when the system had an orbital period of about 0.75 days, very close to the corresponding bifurcation period.

(iii) The numerical calculations simulating the evolution of converging systems, indicate that the ultra-compact binary systems 4U1626-67, G16-29, 4U1916-05 and 1E2259+59, which all have orbital periods < 1 hour), contain secondaries which are most likely severely hydrogen-exhausted (i.e. $X_c \approx 0.0$; Savonije et al., 1985; Nelson et al., 1986; and references therein).

(iv) Cen X-4, a system with an orbital period of 15.1 hour and a most probable secondary-mass of 0.05 to 0.20 $M_\odot$ possibly is a system close to the end of mass transfer, with a mean rate of mass transfer of a few 10^{-11} $M_\odot$/yr (Chevalier et al., 1988). The secondary in the system must have started mass transfer when the binary period P_i was very close to, but longer than P_{bif} and the initial mass of the secondary was then probably higher than 1.5 $M_\odot$.

(v) We further present indications that the observed characteristics of Sco X-1 may be in accordance with a present evolutionary phase at the very end of a rapid mass-transfer phase, which occurs whenever the initial mass ratio q is > 1. The initial secondary and primary component-masses can then have been 1.5 and 1.0 $M_\odot$, respectively.

(vi) Finally, we suggest that the cataclysmic variable GK Per, which has an orbital period of 2 days, is in a stage preceding the formation of a low-mass X-ray binary by accretion-induced collapse of a massive white dwarf. The secondary has a mass of about 0.26 to 0.35 $M_\odot$ and is likely to have developed a He-core of about 0.15 $M_\odot$.

3. Spin-period variation of neutron stars due to mass-accretion (Chapter II).

a. Modelling the spin-up evolution of neutron stars in low-mass close binaries.

The mass lost by the hydrogen burning low-mass star flows through the first Lagrangian point towards the compact component, around which it will form an accretion disk. In Chapter II, we study the evolution of the spin period of the neutron star as a consequence of the accretion of matter with angular momentum. In these considerations, it is essential to know the evolution of both the neutron star magnetic field and the mass-accretion rate, and to employ an appropriate description for the accretion-torques resulting from the interaction between the accretion disk and the magnetosphere (see e.g. Ghosh and Lamb, 1978, 1979). An essential parameter in this analysis is the so-called "equilibrium" spin period, at which the accretion torques and spin-down torques cancel one another.

The evolution of the magnetic field of a neutron star is still a matter of debate, the question being essentially whether the surface magnetic field decays with time or not (Taylor and Stinebring, 1986; van den Heuvel et al., 1986; Kundt, 1988). In this work, we will assume that neutron stars are born with strong magnetic fields of about 10^{12} to 10^{13} Gauss which decay in the course of time. Observations of radio pulsars in low-mass binaries (Kulkarni, 1986, 1987) then indicate that the field decay does not continue indefinitely, but stops when a "bottom"-value of between 5. 10^{8} and about 10^{11} Gauss is attained. It is possible that the strong initial field is the "crustal" field of the neutron star, while the "bottom"-value corresponds with the field associated with the superconducting interior of the star. The crustal field is believed to be formed at the birth of the neutron star and is thought to decay on a timescale of 10^{6} to 10^{7} years (Lyne et al., 1985), until the "bottom"-value is attained (cf. van den Heuvel et al., 1986). Thus, depending on the age of the neutron star, either the crustal or the core field are observed.

For the evolution of the mass-accretion rate onto the neutron star, the results of Chapter I are used. As long as the accretion-rates onto

the neutron star are not super-Eddington, one may assume that all mass lost by the low-mass companion is accreted by the neutron star. Since the evolution of the numerically obtained mass-accretion rates may be quite different from those obtained (semi-) analytically (see e.g. Webbink et al., 1983), it appeared to be interesting to extend and improve previous spin-evolution calculations, such as those performed by de Kool and van Paradijs (1987).

Qualitatively, the spin-evolution of a neutron star, formed during an accretion-induced collapse of a massive white dwarf, can be divided into three phases:

1) spin-down due to magnetic dipole radiation during the detached phase following the accretion induced collapse;

2) spin-up and/or spin-down due to mass-accretion when the mass-transfer phase resumes;

3) as in 1) when the hydrogen envelope of the donor star has been exhausted, and mass-transfer is terminated.

According to our calculations, the spin-evolution of the neutron star during the mass-accretion phase can in general be divided into three phases:

i) evolution "in equilibrium" (i.e. with a spin-period equal to the "equilibrium" period) when the magnetic field of the neutron star has not yet decayed significantly. This phase lasts for about one field decay timescale.

ii) evolution "out of equilibrium" (i.e. slower than with the "equilibrium" period) when the magnetic field is rapidly decaying, until its bottom-value is attained. This phase can last for a few times 10^7 years, depending on the precise value of the core field.

iii) evolution "in equilibrium" again, when the bottom-field has been reached. During this phase, the spin-evolution of the neutron star is completely determined by the evolution of the mass-accretion rate. Both spin-up and spin-down phases can occur, depending on the rate of change of the mass-accretion rate. As a consequence of long-lasting phases of a decreasing mass-transfer rate, the neutron star can spin down on a timescale of several times 10^9 years.

If, however, the accretion phase is relatively short, due to a large accretion rate and a low amount of envelope mass available for

transfer, it is possible that the neutron star does not evolve through phase iii) or even phase ii).

b. Applications to observed systems.

The neutron star in the low-mass binary radio pulsar system PSR 1855+09, which has an orbital period of 12.3 days, rotates with a period of 5.36 milliseconds and has an approximate magnetic field strength of 3.3 10^8 Gauss. The white dwarf companion has been observed and has a mass of about 0.2 to 0.4 $M_\odot$ and an effective temperature of about 5900 K (Wright and Loh, 1986), which indicates that it is very old (several times 10^9 yrs). Consequently, the neutron star is also very old and its observed magnetic field strength is the strength of the core field. From the numerical calculations performed by Pylyser and Savonije (1988a), the evolution of the mass-transfer rate in the previous low-mass X-ray binary phase can be inferred and used in the spin period calculations for the neutron star in this system. Assuming a standard formation-scenario for the system, i.e. the formation of a neutron star in an accretion induced collapse followed by a mass-transfer phase until the hydrogen envelope is exhausted, and a standard decay scenario for the magnetic field of the newly-formed neutron star, it is possible to model the evolution of the spin period of the neutron star, leading to the presently observed rotational status of the pulsar. Our calculations indicate that a minimum amount of mass of 0.04 $M_\odot$ must have been accreted by the neutron star at a rate of at least about 7. 10^{-10} $M_\odot$/yr, which indirectly suggests that the initial mass of the donor star must have been less than 1.5 $M_\odot$.

The spin period and period derivative of the low-mass binary radio pulsar PSR 1831-00, which has an orbital period of about 1.8 days, indicates that the neutron star in this system has an age of a few 10^9 years. The bottom-field in this system is found to be 8. 10^{10} Gauss. We find that the mass-transfer rate in a low-mass X-ray binary, which terminates mass-transfer with an orbital period of 1.8 days is almost a factor 10 too low to spin up a magnetized neutron star to a period of about 0.52 seconds, as observed, since the expected equilibrium period

is > 1 second. We suggest an alternative formation-scenario in which the neutron star was formed during an accretion-induced collapse after which it did not accrete matter any more. This is expected to be the case if the rotational period of the newly formed neutron star was in the millisecond range, a scenario in which the remaining hydrogen-envelope of the orbiting secondary is "evaporated" and lost from the system (van den Heuvel and van Paradijs, 1988; Phinney et al., 1988; Kluźniak et al., 1988; Ruderman et al., 1988).

Finally, in the last part of section II.1, we briefly analyze the observed rotational characteristics of the X-ray pulsars Her X-1, GX1+4, 4U1626-67 and 1E2259+59 in the context of neutron-star spin-period evolution.

c. On the relation between low-mass X-ray binaries and binary radio pulsars.

A determination of the birth-rate of wide low-mass X-ray binaries and, independently, low-mass binary radio pulsars by Kulkarni and Narayan (1988) indicates that possibly not all low-mass binary radio pulsars have to be the remnants of low-mass X-ray binaries. This holds especially for the relatively short orbital period systems (i.e. P_{orb} about a few days or less).

As the mean characteristics of wide low-mass X-ray binaries and their mass-transfer rates, obtained from our numerical calculations, are quite different from those obtained with analytical methods, we repeated the analysis by Kulkarni and Narayan, using our new results. We show that the discrepancy between the birth rates of both kind of short orbital period systems is considerably smaller than that obtained by Kulkarni and Narayan (1988; i.e. a factor 40 versus 300-2000, respectively). The disrepancy may possibly even be insignificant, if we assume that part of the hydrogen-rich envelope of the secondary companion, instead of being transferred towards the neutron star can be "evaporated" from the secondary by the large impinging energy flux of a nearby millisecond pulsar. The X-ray lifetime of a low-mass X-ray binary can thereby be shortened significantly, while simultaneously, the radio lifetime of the system increases. This brings the birthrates of the two types of systems in better agreement.

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