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LOW-MASS BINARIES AND STELLAR DYNAMOS

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ABSTRACT

We examine the possibility of dynamo action in a low-mass star, component of a low-mass binary (LMB). Our analysis is based on the calculations of a nonconservative evolution of a system initially consisting of a $1.4 M_{\odot}$ neutron star and a $1 M_{\odot}$ companion. We perform our calculations for three cases, where the companion is initially a main-sequence star ($X_c = 0.45$) or a star with a small degenerate helium core of mass $M_{\text{He}} = 0.026$ or $0.06 M_{\odot}$, and where a companion fills its Roche lobe at the orbital period of a system $P_{\text{orb}} \sim 9.6, 21.6$, and 25.4 hr, respectively. We show that to maintain LMB evolution driven by stellar “magnetic braking,” an efficient mechanism producing large-scale surface magnetic fields in a donor star is needed. We discuss the relevance of the dynamo mechanisms, including those with cycles, to the late stages of evolution of a donor star in an LMB.

Subject headings: binaries: close — MHD — stars: evolution — stars: magnetic fields — stars: mass loss — stars: neutron

1. INTRODUCTION

Ryba & Taylor (1991) and Arzoumanian, Fruchter, & Taylor (1994) have found that the orbital period derivative of PSR 1557+20 has changed sign and that PSR 1557+20 undergoes quasi-cyclic orbital period changes. They interpret their data as a possible indication of magnetic activity in a low-mass companion. Recently, Smale (1994) has also pointed out that there is some evidence that the period changes observed in several low-mass X-ray binaries (LMXBs) may be cyclic, with proposed cycles of ~ 10 yr. However, this evidence can become convincing only after further long-term X-ray monitoring of these systems. Smale also stated that the possible causes of the orbital period changes may be solar-type cycles in the companion and X-ray heating of the companion by the flux from the compact object.

In his assessment of the problem, Wijers (1994, 1995) has discussed that the common cause of both the orbital period variability and the large rates of mass loss in compact binaries with late-type companions is the enhanced stellar activity. He has suggested that the eclipsing radio pulsars PSR 1557+20 and 1744–24A, the X-ray binaries 4U 1820–30, EXO 0748–676, and X1822–371, cataclysmic variables and CV-like systems, RS Canum Venaticorum stars, and Algol-type eclipsing binaries belong to the class of close low-mass binaries (LMBs) in which a binary member undergoes stellar activity (see also Wijers & Paczyński 1993). Earlier, Applegate & Patterson (1987) also proposed that a variable quadrupole moment produced by magnetic activity in the outer convection zone of one of the stars in a close binary may be responsible for the orbital period changes over time of order 10 yr. In their recent model for the PSR 1557+20 system, Applegate & Shaham (1994) have suggested that the magnetic activity and the wind driven by the pulsar irradiation result in a torque on the

spin of the companion (see also Sarna, Lee, & Muslimov 1994). This torque holds the companion out of synchronous rotation, causing tidal dissipation of energy. The crucial point of their model (see also § 2.3.2 for a relevant discussion) is that the progenitor of a low-mass companion has a mass of 0.1 – $0.2 M_{\odot}$ (orbital period ~ 2 hr) when the conversion to tidal power and magnetic activity of the progenitor begin (see also Applegate & Patterson 1987).

In this paper, we investigate the plausibility of dynamo operation in low-mass companions of close LMBs. We also explore the relevance of cyclic dynamos to the magnetic activity presumably occurring in some LMXBs and LMBs with radio pulsars. In § 2, we present a brief overview of magnetic stellar dynamos and analyze physical conditions relevant to the dynamo action in a low-mass companion of an LMB. Section 3 summarizes our principal findings.

2. ANALYSIS AND RESULTS

2.1. Evolution of LMBs and “Magnetic Braking”

It is generally believed (see Bhattacharya & van den Heuvel 1991 for a review) that evolution of LMBs with orbital periods $P_{\text{orb}} \lesssim 12$ hr is mostly driven by angular momentum losses due to emission of gravitational waves and to “magnetic braking.” The latter dominates after the binary orbit has shrunk enough and mass transfer begun. It seems therefore quite natural to assume (see references cited in § 1) that the irregularities in the evolution of such binaries (characteristic evolution time $\sim 10^8$ – 10^9 yr) occurring over very short times (e.g., $\lesssim 10$ yr) may be attributed to corresponding variations in magnetic stellar activity and mass loss by a companion.

In calculations of orbital evolution of close LMBs, it is usually assumed that the spin motion of a donor star is tidally locked with its orbital motion. It is thought, therefore, that the loss of spin angular momentum by a donor star (owing to magnetic stellar wind) is recovered by a tidal torque from a compact component (e.g., a neutron star or white dwarf) at the expense of orbital motion. As a result of such evolution, the total orbital angular momentum of a

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system decreases while the angular velocity of a donor star monotonically increases. Also, it is thought that the theory of magnetic braking developed for a single star is applicable to a star in a close binary system. In addition, it is quietly assumed that Skumanich's (1972) empirical relation (for the secular slowing down of stellar rotation) that has been found for single stars with relatively slow rotation can be extrapolated to rapidly rotating stars spinning up in close binaries. In this paper, we emphasize that these assumptions and those appealing to the dynamos, presumably operating in late-type dwarf stars, need to be critically examined in the case of close LMBs.

2.2. Magnetic Activity, Cycles, and Dynamo Action in Stars

2.2.1. General Overview

The *Einstein* X-ray observations (Vaiana et al. 1981) confirmed that all late-type dwarf stars possessed coronae and that the degree of activity increased with the stellar angular velocity (see Walter 1981; Pallavicini et al. 1981). According to the analysis by Vaughan et al. (1981), the 10–12 yr activity cycles are shown almost exclusively by stars with rotational periods longer than ~ 20 days.

There are two basic mechanisms for producing cyclic fields (see, e.g., Parker 1979; Cattaneo, Hughes, & Weiss 1991): dynamo action, in which both poloidal and toroidal components of the field reverse after each half-cycle, and an oscillation, where a reversing toroidal field is generated by shearing a nonreversing poloidal component.

Let us briefly summarize the principal conclusions of the dynamo models of cyclic activity. The efficiency of the standard α - ω dynamo depends on the interplay between the velocity fields owing to stellar differential rotation (ω -effect) and cyclonic convection (α -effect) in the presence of a magnetic field (for a general introductory review, see, e.g., Parker 1979; Weiss 1994; Wilson 1994). The balance between the effects of convection and rotation is characterized by the Rossby number

$$\text{Ro} = (\Omega \tau_{\text{con}})^{-1}, \quad (1)$$

and the critical parameter that determines dynamo action is the dynamo number

$$N_D \approx \text{Ro}^{-2}. \quad (2)$$

Here Ω is the stellar angular velocity and τ_{con} is the convective turnover time.

The observations confirm (see, e.g., Montesinos & Jordan 1993 and references therein) that magnetic activity does depend on Rossby number. Young, rapidly rotating stars with extensive convection zones have low Rossby numbers and show strong but irregular activity. However, cyclic activity appears only in older stars that have significant, but not too extensive, convection zones and rotation periods longer than 20 days (large Rossby numbers).

In a rapidly rotating star, the differential rotation (radial shearing) may not be large, and the α -effect may dominate the ω -effect. The dynamo action in this case may occur in the so-called α^2 - ω , or α^2 , modes, rather than in the α - ω mode. The α - ω dynamo is generally thought to operate in a layer or shell below the stellar convection zone, but in fully convective late M-type stars, there is no possibility of a shell dynamo. Thus the strong but disordered activity exhibited by these stars may be ascribed (see, e.g., Weiss 1994 and references therein) to a fibril dynamo, acting in some region of the convective star operating in the α^2 mode. Using the data of the *ROSAT* All-Sky Survey, Fleming et al. (1993)

have undertaken an attempt to probe the nature of the magnetic dynamo and coronal activity in the very late M dwarfs (also known as very low-mass fully convective stars). They infer the existence of the magnetic field in these stars from strong coronal emission, which may indicate that a fibril dynamo is just as efficient in producing magnetic flux as a shell dynamo. However, as Fleming et al. have correctly pointed out, the fibril dynamo may generate a magnetic field less efficiently, and the coronal heating efficiencies just increase for these stars to produce high levels of X-ray flux. It is expected that the irregular behavior (a regime with several interfering modes) occurs when the dynamo number is large (Parker 1971). Therefore, as has been pointed out by Knobloch, Rosner, & Weiss (1981), it is dangerous to extrapolate from linear results into the nonlinear regime, and different dynamo mechanisms may operate in the high- and low- Ω regimes (see also Durney, Mihalas, & Robinson 1981). For example, in the high- Ω regime, the Coriolis force may strongly affect the convective motions, making the convective cells elongated parallel to the axis of rotation. As has been shown by Jones, Galloway, & Roberts (1990), in the presence of a toroidal magnetic field B_{tor} , the mode of convection is determined by the Elsässer number

$$N_E = \frac{B_{\text{tor}}^2}{2\mu\rho\eta_m\Omega}, \quad (3)$$

where μ is the magnetic permeability, ρ is the density of matter, and η_m is the magnetic diffusivity. For small values of N_E , banana cells are favored, but for values greater than some critical value (~ 1), the convection pattern transforms into the azimuthal rolls centered about the rotation axis. In the nonlinear dynamos, it is also worthwhile to introduce the parameter that characterizes the influence of rotation on the dynamics, the Taylor number

$$N_T = 4\Omega^2 d^4 / \nu^2, \quad (4)$$

where d is the thickness of convection zone and ν is the kinematic viscosity produced by turbulent motions. Another useful parameter, characterizing the relative magnitudes of magnetic viscosity and heat conductivity, is the magnetic Prandtl number, given by

$$N_{\text{mP}} = \eta_m / \kappa, \quad (5)$$

where κ is the thermal diffusivity.

In his numerical analysis of the nonlinear regime of dynamos driven by convection in a rotating spherical shell, Gilman (1983) found that the fraction of total kinetic energy that is in the form of differential rotation is an important parameter for determining what kind of dynamo action may be allowed. Referring to the convection experiments, he summarizes that, at low rotation, the convection is slightly modified and a small differential rotation develops. As the rotation rate increases, the differential rotation fraction of the kinetic energy increases because the Reynolds stresses, produced by the Coriolis forces, increase. But eventually a peak is reached, beyond which the differential rotation fraction decreases again. This is because the rotation starts to suppress the convection itself. Finally, the rotation suppresses the convection, leaving no motion. Gilman has demonstrated the occurrence of different kinds of dynamos in the "regime diagram," which represents the plot of the inverse magnetic Prandtl number $q = N_{\text{mP}}^{-1}$ as a function of, say, Taylor number N_T . Though this diagram is rather speculative, it shows clearly that the region favorable for dynamos with cycles is relatively small. This region is char-

acterized by a substantial fraction ($\sim 30\%$ – 40%) of the total kinetic energy that is in the form of differential rotation. At low Taylor numbers there is no dynamo because rotation is too weak to induce much helicity (α -effect) or differential rotation, while at high Taylor numbers there is no dynamo action because the convection is suppressed enough by rotation. Other regions in the “regime diagram” are occupied by dynamos without cycles (because the differential rotation for those regions is too weak).

2.2.2. Concept of Modified α - ω Dynamo

The original idea of the α - ω dynamo was formulated by Parker (1955) and then developed in many papers (see, e.g., Parker 1970, 1979; Steenbeck & Krause 1966; Steenbeck, Krause, & Rädler 1966; Moffat 1978; Krause & Rädler 1980; Vainshtein 1970; Vainshtein & Zeldovich 1972; Zeldovich, Ruzmaikin, & Sokoloff 1983; and references therein). However, during the past five years, some significant modifications of the standard α - ω dynamo have been made, and we shall now briefly discuss these modifications and their possible impact on the issue of the magnetic activity in low-mass companions of LMBs.

An essential element of dynamo theory is the presence of enhanced (turbulent) diffusion of the magnetic field (see, e.g., Vainshtein, Parker, & Rosner 1993a). The separation of magnetic loops from the main toroidal field to produce (due, e.g., to α -effect) the generated large-scale poloidal field requires a diffusive process that operates on times much shorter than half the dynamo period (e.g., ~ 11 yr for the Sun). In the absence of enhanced dissipation, strong toroidal fields will block the further generation of fields and hence suppress the functioning of the dynamo cycle. In the standard dynamo theory, α -effect suppression usually arises (see Stix 1972) when magnetic fields are assumed to attain equipartition value, defined by equality between the magnetic energy density and the local kinetic energy density of matter.

Recently, the modification of a sequence of physical events that eventually results in an effective α -process has been suggested (see Vainshtein et al. 1993a and references therein). This modification is based on the important role the turbulent diffusion may play in the problem of magnetic dynamos, as has recently been discussed by Vainshtein & Rosner (1991), Cattaneo & Vainshtein (1991), Vainshtein & Cattaneo (1992), and Tao, Cattaneo, & Vainshtein (1993). These authors have shown that classical dynamo theory, when self-consistently extended to the nonlinear regime, predicts that the magnetic fields can become dynamically important on small spatial scales and that even very weak large-scale magnetic fields (whose strength is far below the local equipartition value of field strength) can suppress turbulent diffusion without considerably affecting the turbulence itself. This back reaction of the magnetic fields on small-scale motion is essential to dynamo theory and can completely modify the nature of field amplification (Vainshtein et al. 1993a; see also discussion in Chakrabarti, Rosner, & Vainshtein 1994). However, the problem is that the total magnetic flux of the azimuthal magnetic field in a thin layer below the convection zone may be so great as to suppress the eddy diffusion and cyclonic α -effect (for further discussion, see Tao et al. 1993; Vainshtein et al. 1993b; Jones & Galloway 1993) that are essential to the operation of dynamos. Parker (1993) suggested that dynamo operation may yet be effective and self-consistent provided that

the eddy diffusivity is suppressed inversely with the magnetic energy density. (Note that the requirement of eddy diffusivity follows from the condition that the characteristic period τ_{cyc} of a dynamo is of the order of $\tau_{\text{cyc}} = L^2/4\eta$ in a field with characteristic scale L subject to the eddy diffusivity η .) Then, Parker envisages, so long as η is not suppressed by more than $1/B_{\text{tor}}^2$, the 22 yr solar dynamo period τ_{cyc} can be maintained in the presence of a strong azimuthal field B_{tor} , and if we require a total azimuthal flux $\Phi_{\text{tor}} = hB_{\text{tor}}$ per unit length in the north-south direction, we have to set $L = h$ (where h is the thickness of a layer in which the vertical shear $\partial\Omega/\partial r$ is concentrated) and obtain the result $\tau_{\text{cyc}} = \Phi_{\text{tor}}^2/4\eta B_{\text{tor}}^2$. The reduced eddy diffusivity thus leads to a reduced scale h in a self-consistent manner. This aspect of modification of dynamos may have interesting implications for low-mass companions of LMBs. For example, the effect of suppression of eddy diffusivity would be much more pronounced for these stars, if their magnetic cycles are indeed as long as ~ 10 yr. Also, at the very late stages of evolution, the value of h ($\sim H_p$, the pressure scale height at the base of the convection zone) may decrease by a factor of 10^2 (e.g., as in the present study, for a companion with $0.026 M_{\odot}$ helium core), which would require substantial suppression of eddy diffusivity to explain cycles of order 1–10 yr.

Another modification that has recently been introduced (Parker 1992) is that the stellar magnetic fields may be regenerated by a “fast dynamo” of some form, which schematically acts in the following way: “The nonuniform rotation generates the strong azimuthal field, and the rest of the dynamo action is provided by reconnection of the azimuthal flux bundles under the action of their own stresses. Then the hydrodynamic rotation of free loops into meridional planes involves little or no energy change, where again reconnection, driven primarily by magnetic stresses, provides the large-scale poloidal field” (Parker 1992, p. 137). In contrast to the standard α -effect, when the convective cells stretch strong toroidal fields to form a loop, which then is turned by the Coriolis force into meridional planes, in the fast dynamo (see Parker 1992; Vainshtein et al. 1993a) the loops are created and separated during the mixing and reconnection of toroidal fields of opposite polarities; only after that are the free loops advected by convective cells and turned by the Coriolis force to form poloidal loops. This dynamo regime may also be important for the low-mass stars under discussion, since the dynamo numbers for these stars are expected to be extremely high, and it is very likely that higher order magnetic modes can be generated. The shearing of these small-scale poloidal fields by differential rotation may result in production of toroidal fields with opposite polarities, which are needed for the aforementioned dynamo regime. Recently, Gilbert, Otani, & Childress (1993) have explored numerically the saturation of a fast dynamo using some constrained models. This is a first step in analyzing the saturation mechanisms, and the results of such study may have a serious impact on our understanding of the resulting spatial structure and temporal behavior of the field.

2.3. Evolution of Low-Mass Donor: Tracing Down Its Magnetic Activity

2.3.1. Basic Assumptions and Method of Calculation

In this paper, we employ evolutionary calculations performed for a binary system initially consisting of a $1.4 M_{\odot}$ neutron star and a $1 M_{\odot}$ companion. We consider three

cases, in which the companion is either a typical main-sequence star (with $X_c = 0.45$) or a star with a degenerate helium core of mass 0.026 or $0.06 M_\odot$. In the corresponding evolutionary sequences (see Figs. 1, 2), the orbital period decreases from 9.6 to 6 hr (cf. Muslimov & Sarna 1993, hereafter MS93), from 21.6 to ~ 1 hr, and from 25.4 to 10.8 hr, respectively, and the evolutionary sequences end up at masses of the donor star of ~ 0.3 , ~ 0.1 , and $\sim 0.15 M_\odot$, respectively. Note that the systems with longer initial orbital periods (~ 1 day) evolve toward shorter orbital periods because their initial periods are less than a so-called bifurcation initial orbital period (for details see, e.g., Pylyser & Savonije 1989; Sarna, Marks, & Smith 1995), and the corresponding evolutionary sequences are therefore of particular interest for our study. (For our evolutionary sequences [for stars with small helium cores], the value of the bifurcation initial orbital period is of order 1.4 – 1.5 days.)

In our calculations, we assume that semidetached evolution is nonconservative. This means that the total mass and total angular momentum of a system are not conserved. The loss of mass and angular momentum from a system are characterized by two parameters, f_1 and f_2 . The former is defined as a ratio of the mass lost from a system to the mass lost by a donor star, and the latter is the efficiency of loss of the orbital angular momentum during the mass transfer phase (see, e.g., MS93; Sarna & De Grève 1994). In our calculations, at the beginning of a semidetached phase, the values of f_1 and f_2 are normalized to unity. We assume the loss of orbital angular momentum is a result of the magnetic braking of a donor star possessing a convective envelope. For a system with the shortest orbital period, during the final stages of evolution, we also take into account the loss of orbital angular momentum due to emission of gravitational radiation (see Landau & Lifshitz 1971).

The stellar models for a donor star have been computed with a standard stellar evolution code based on the Henyey-type code of Paczyński (1970), which has been adapted to low-mass stars. To treat the convection, we have employed the mixing-length algorithm proposed by Paczyński (1969). For calculations of the radiative transport, we have used the opacity tables of Iglesias, Rogers, & Wilson (1992). Where these tables are incomplete, we have filled the gaps using the opacity tables of Huebner et al. (1977). For temperatures less than 6000 K, we use the opacities given by Alexander, Johnson, & Rypma (1983). The contribution from conduction provided in the opacity tables of Heubner et al. has been added to the tables in which it is missing. Finally, we assume Population I chemical composition ($X = 0.7$, $Z = 0.03$) for the mass-losing component.

For the case of the initially main-sequence donor star, the mass transfer occurs on a thermal timescale, and we assume that a neutron star spins up until it reaches a spin period of order 1.5 ms. We also assume that the hard X- and γ -ray radiation from the millisecond pulsar illuminates a donor star, resulting in additional heating of its photosphere (in a manner described by Harpaz & Rappaport 1991, 1994; MS93; Muslimov & Sarna 1995, hereafter MS95; D'Antona & Ergma 1993). The essential point is that additional heating provides a relatively high ($\sim 0.5 \dot{M}_{\text{Edd}}$) rate of mass loss by a donor star (cf. MS93).

It must be pointed out that the rate of loss of orbital angular momentum owing to magnetic braking of a donor star is usually calibrated by a parameter value λ (see, e.g.,

Verbunt & Zwaan 1981; Iben & Tutukov 1984) that monotonically increases from ~ 0.7 to ~ 1.7 during the course of evolution. In this paper we have calculated evolutionary sequences with allowance for the dynamo maintenance of the magnetic field in a low-mass star. In our calculations, in the formula for magnetic braking, we do not use the standardly employed λ -parameter. Instead, we calculate the equipartition value of the magnetic field strength B_{eq} generated at the base of the stellar convection zone, and then, in the formula for magnetic braking, we use the following value for the surface magnetic field strength:

$$B_{\text{sur}} \sim \frac{r_b H_p}{R_c^2} B_{\text{eq}}, \quad (6)$$

where r_b is the inner radius of the convection zone, H_p is the pressure scale height at the base of the convection zone, and R_c is the radius of the companion. In our derivation of equation (6), we have assumed that the magnetic flux of the toroidal magnetic field (which is important for the generation of poloidal fields in the context of standard α - ω dynamos; see, e.g., Parker 1979), generated at the base of the convection zone, $\Phi_{\text{tor}} \sim B_{\text{eq}} \pi [(r_b + \frac{1}{2} H_p)^2 - (r_b - \frac{1}{2} H_p)^2] = B_{\text{eq}} 2\pi r_b H_p$, is equal to the magnetic flux of a large-scale poloidal field through the stellar surface, $\Phi_{\text{pol}} \sim B_{\text{sur}} 2\pi R_c^2$.

Equation (6) implies therefore that the large-scale poloidal magnetic field is rather efficiently maintained by dynamo action in a companion during its evolution in an LMB. The surface value of the field strength calculated with equation (6) has been used in the standard formula for magnetic braking to derive the rate of loss of orbital angular momentum (assuming synchronous rotation) owing to magnetic braking:

$$\left(\frac{dJ}{dt} \right)_{\text{MB}} = -3 \times 10^{-7} \frac{1}{\lambda^2} \frac{(m_c + m_{\text{ns}})^2 r_c^4}{m_{\text{ns}} a^5} \text{ yr}^{-1}, \quad (7)$$

where J is the orbital angular momentum of a system, m_c and m_{ns} are the masses (in solar units) of the companion and neutron star, respectively, and r_c and a are the radii of the companion and orbital separation (both in solar units), respectively.

The explicit expression for the λ -parameter in equation (7) now reads

$$\lambda \sim 0.5 \frac{r_c}{r_{b9}} \left(\frac{m_c}{\rho_b} \right)^{1/2} H_{p9}^{-2} T_6^{1/4} N_D^{1/2}, \quad (8)$$

where $H_{p9} = H_p / (10^9 \text{ cm})$, $T_6 = T_{\text{ph}} / (10^6 \text{ K})$ with T_{ph} the photospheric temperature of the companion, ρ_b is the mass density at the base of convection zone in g cm^{-3} , and $r_{b9} = r_b / (10^9 \text{ cm})$.

2.3.2. Main Results and Discussion

Equation (8) shows that the efficiency of magnetic braking is rather sensitively determined by the characteristic density and pressure scale height in a shear layer at the base of the convection zone. For example, in the case of the evolutionary sequence calculated for the initially main-sequence star, the efficiency of magnetic braking increases during evolution mostly because of increase in density of the shear layer. In contrast, in the cases of evolutionary sequences calculated for stars with small helium cores, the efficiency of magnetic braking at very late stages of evolution substantially decreases because the shear layer shifts toward the lower densities. In other words, as our calculations show, for the companion evolving from a main-

FIG. 1.—Evolution of the orbital period as a function of mass of a donor star. The calculations were performed for an initially main-sequence companion (solid curve) and for stars with small helium cores of mass $0.026 M_{\odot}$ (dashed curve) and $0.06 M_{\odot}$ (dot-dashed curve), respectively.

sequence star, the kinetic energy of convective motions near the base of convection zone decreases during evolution, but only by less than a factor of ~ 10 . On the contrary, for the companions evolving from stars with small helium cores, an energy reservoir for dynamo operation diminishes during evolution, at least by a factor of $\sim 10^3$. This is a principal conclusion, and it does not depend on the particular type of dynamo.

The resulting value of the parameter λ , which substantially changes during evolution of a binary, is shown in Figure 3. This figure also shows that the efficiency of magnetic braking for the initially main-sequence star increases during evolution by a factor of ~ 5 – 8 . In the cases of stars with small helium cores, the efficiency of magnetic braking monotonically increases by a factor of ~ 25 during the first $\sim 10^9$ yr. Then, at the very late stages of evolution, it declines by more than a factor of 200. The latter, in fact, means that the magnetic braking is effectively switched off when the mass of a companion has decreased to $M_c \sim 0.1$ – $0.15 M_{\odot}$.

In Figure 4 we show the evolution of the dynamo number N_D , Taylor number N_T , and the inverse magnetic Prandtl number $q = N_{\text{mP}}^{-1}$ as a function of mass of a donor star. The dynamo number for the initially main-sequence star mono-

FIG. 2.—Rate of mass loss by a donor star as a function of time. Other details are the same as in Fig. 1.

FIG. 3.—Calculated value of the parameter λ (see also § 2.3.1) as a function of mass of a donor star. Other details are the same as in Fig. 1.

tonically increases (due mostly to the increase in turnover time) by a factor of 10^2 during its evolution in a binary. For the stars with helium cores, the dynamo number remains practically constant until the mass of a star decreases down to $M_c \sim 0.15 M_{\odot}$. After this point, the dynamo number decreases by more than a factor of 10^3 because of the rapid

FIG. 4.—(a) Dynamo number N_D , (b) Taylor number N_T , and (c) inverse magnetic Prandtl number q as functions of mass of a donor star. Other details are the same as in Fig. 1.

decrease in turnover time caused by the diminishing of the convection zone. Figure 4b also shows that for the star with the $0.026 M_{\odot}$ helium core (*dashed curve*), the effects of rotation on convective motions substantially increase at the stellar mass $M_c \lesssim 0.15 M_{\odot}$. In addition, Figure 4c shows that for the cases in which the companion has a small helium core (*dashed, dot-dashed curves*), at the stellar mass $M_c \lesssim 0.15 M_{\odot}$ the inverse magnetic Prandtl number q increases mostly as a result of the decrease in density of the shear layer (because in degenerate plasma $q \propto \rho$). For the case of the main-sequence donor star (see Fig. 4c; *solid curve*), the number q decreases as a result of an increase in density of the shear layer, because in this case the stellar plasma is nondegenerate and $q \propto \rho^{-1}$. Our calculations may indicate therefore that the standard α - ω dynamo is unlikely to operate in a donor star of mass $M_c \lesssim 0.2 M_{\odot}$ that has evolved from a star with a small helium core, and that the possibility of dynamo action in a low-mass donor star may seriously constrain the evolutionary scenarios for some LMBs.

We have demonstrated that for the cases in which a donor star has a small helium core, at the very late stages of evolution of a system, the efficiency of magnetic braking substantially decreases. This means that it would be difficult to explain the large values of $\dot{P}_{\text{orb}}$ reported for some LMXBs (see, e.g., Smale 1994) in terms of these evolutionary sequences. On the contrary, the large variations in $\dot{P}_{\text{orb}}$ can easily be reproduced for an LMB initially containing a main-sequence companion (see also MS95). The quasi-cyclic changes in the orbital period may be caused either by stellar magnetic cycles or by episodes of discrete mass loss by a donor star similar to those discussed by MS95, but occurring on much shorter timescales.

In the present study, it is worthwhile to estimate the longest diffusive time for a star (the ohmic time for decay of a dipole mode in a radiative core):

$$t_D = \frac{4\sigma r_0^2}{\pi c^2} \sim 1.7 \times 10^{11} \left(\frac{r_0}{R_{\odot}} \right)^2 \left(\frac{\rho_0}{10^2 \text{ g cm}^{-3}} \right) \text{ yr}, \quad (9)$$

where σ is an electrical conductivity of matter, r_0 is a radius of the radiative core, and ρ_0 is the mass density in a stellar core. During the very early stages of evolution of a donor star, its radiative core cools down to $\sim 10^7$ K, and the electrical conductivity of matter in the core becomes determined by the scattering of degenerate, nonrelativistic electrons from ions. In our numerical estimate in equation (9), we have used the value of electrical conductivity $\sigma \sim 8 \times 10^{17} [\rho / (10^2 \text{ g cm}^{-3})] \text{ s}^{-1}$ (see, e.g., Hubbard 1966). Note that, both for the cases of the initially main-sequence star and stars with helium cores, the ohmic decay time remains very long, $\sim 10^{10}$ yr, during the evolution time, $\sim 10^8$ and $\sim 10^9$ yr, respectively. However, at the very late stages of evolution, the ohmic decay time may become comparable to the evolution time. At this stage, any dynamo (if it operates) should enter a “starving” regime. The very late evolution of a system may therefore be driven by magnetic braking of a low-mass companion if the dynamo very efficiently maintains the large-scale poloidal field of a star. Then the dynamo-enhanced component of the magnetic field may eventually provide a sufficient magnetic braking.

If the “regime diagram” (see § 2.2.1) proposed by Gilman (1983) remains self-similar even for very rapidly rotating low-mass stars in LMBs, then our calculations may indicate

that, during its evolution in a binary, a low-mass companion remains in the domain where the α -effect and differential rotation are too small because rotation reduces convection. Therefore, without substantial differential rotation, the dynamos, including those with cycles, are impossible in this domain of the “regime diagram.”

Applegate & Shaham (1994) have suggested that the tidal dissipation in a progenitor of the low-mass companion of the PSR 1957+20 system is responsible for the subsequent magnetic activity of the companion (see also § 1). They have found that the maximum of tidal luminosity and corresponding heating occurs in the outer part of a star containing $\sim 10\%$ – 20% of the stellar mass. However, for the assumed mass of a progenitor (~ 0.1 – $0.2 M_{\odot}$), at least this much of the star must be convective. Note that the dynamical tides most efficiently excite the gravity modes and that the power in these modes increases inward. In addition, in a convection zone of a star these modes cannot be excited at all (see Sarna et al. 1994 for a relevant discussion). The latter means that the efficiency of the mechanism discussed by Applegate & Shaham may be grossly overestimated. Alternatively, one can assume that rapid rotation of a low-mass progenitor (and evaporation of its surface layers by energetic radiation and relativistic particles from a neutron star) partly suppresses the convection while tidal torque from a neutron star generates strong differential rotation at the base of the convection zone, which may eventually result in the enhanced magnetic activity of the companion. Our analysis may also suggest that if a progenitor of the low-mass companion of the PSR 1957+20 system is a star with a small helium core (see, e.g., the evolutionary sequence for the star with $0.06 M_{\odot}$ helium core presented above), then the quasi-cyclic changes in the orbital period of this system may be produced by the shearing of the fossil poloidal magnetic field (or of the poloidal magnetic field generated by the dynamo action in a progenitor) of the companion. Interestingly, the effect of shearing of the large-scale poloidal magnetic field is probably being observed in some RS Canum Venaticorum systems (see Donati 1994 and references therein).

3. SUMMARY AND CONCLUSIONS

We have calculated three evolutionary sequences for a binary initially consisting of a canonical neutron star of mass $M_{\text{ns}} = 1.4 M_{\odot}$ and a companion of mass $M_c = 1 M_{\odot}$ that has been taken to be a typical main-sequence star and a star with a 0.026 and $0.06 M_{\odot}$ degenerate helium core, respectively. As a result of these evolutions, a low-mass companion ($M_c \lesssim 0.1$ – $0.2 M_{\odot}$) orbiting a neutron star would be left behind. The final periods of these LMBs would be $P_{\text{orb}} \sim 6, 1$, and 11 hr, respectively. The possibility of dynamo operation and of enhanced magnetic braking may be crucial for the very late evolutions of these systems. The LMBs consisting of a neutron star and a degenerate companion of mass $M_c \sim 0.03$ – $0.05 M_{\odot}$ and having both extremely short ($\lesssim 1$ hr) and relatively long (~ 9 – 12 hr) orbital periods may be a result of such sped-up (due to enhanced magnetic braking) evolution. In the case of an initially main-sequence companion, an LMB with a nondegenerate companion of mass $M_c \lesssim 0.1 M_{\odot}$ and orbital period ~ 6 – 7 hr may also be a product of the sped-up evolution.

Our calculations of the magnetic braking are based on a formula (eq. [6]) that relates the equipartition value of the

toroidal magnetic field generated at the base of convection zone with the surface value of the large-scale poloidal field. However, we warn the reader that this simplified formula may be incorrect for the very late stages of evolution of a companion. Also, a detailed physical picture of this late evolution is by no means understood. In addition, the dynamo theory is completely unexplored for the situations that have been discussed in this paper. Despite all these difficulties, we suggest that, in low-mass companions in close binaries, a kind of nonlinear dynamo may operate provided that in these stars a strong differential rotation maintaining the azimuthal field is continually sustained by external forces. For example, such a differential rotation may be produced by

1. A faster synchronization of the surface layers (experiencing a larger tidal torque per unit mass) than of the interiors of a star (see, e.g., Zahn 1969);
2. The circulation flows due to an asymmetric heating of a donor star by a neutron star;
3. A superposition of the tidally excited torsional oscillations.

We have found that the physical conditions in the companions of mass $M_c \lesssim 0.1\text{--}0.2 M_\odot$ that have been evolved from stars having small degenerate helium cores are less favorable for the occurrence of dynamos. The conditions for the occurrence of cycles in the low-mass companions are, in

general, even more speculative and need special analysis within the framework of the relevant theoretical models. We propose to perform such an analysis in the future.

We also conclude that, if any dynamo producing large-scale surface magnetic fields operates in a low-mass companion with a thick convection zone, then this dynamo should be very efficient (see also MS95). The partial suppression of the convection in a donor star by a rapid stellar rotation and/or by additional heating (due to illumination from a neutron star) of its surface layers is a factor that may potentially enhance the efficiency of dynamo action at the late stages of evolution. Further evidence in favor of the existence of magnetic cycles in the low-mass companions of LMBs would challenge both the existing dynamo theories and evolutionary scenarios for LMBs, including LMXBs.

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