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Magnetic activity and evolution of Algol-type stars – II

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ABSTRACT

We examine the possibility of probing dynamo action in mass-losing stars, components of Algol-type binaries. Our analysis is based on the calculation of non-conservative evolution of these systems. We model the systems U Sge and β Per where the more massive companion fills its Roche lobe at the main sequence (case AB) and where it has a small helium core (early case B) respectively. We show that to maintain evolution of these systems at the late stages which are presumably driven by stellar 'magnetic braking', an efficient mechanism for producing large-scale surface magnetic fields in the donor star is needed. We discuss the relevance of dynamo operation in the donor star to the accelerated mass transfer during the late stages of evolution of Algol-type binaries. We suggest that the observed X-ray activity in Algol-type systems may be a good indicator of their evolutionary status and internal structure of the mass-losing stellar components.

Key words: binaries: close – stars: evolution – stars: individual: β Per – stars: individual: U Sge – stars: magnetic fields – X-rays: stars.

1 INTRODUCTION

Einstein X-ray observations (Vaiana et al. 1981) supported a general concept that all late-type dwarf stars possess coronae, and that the degree of activity increases with the stellar angular velocity (see Pallavicini et al. 1981 and Walter 1981). A summary of main observational data on the activity of late-type stars, and a discussion of the data related to the stellar activity, magnetism and dynamos are given by Vaiana & Sciortino (1986) and Jordan (1991) respectively. It is believed that the stellar cyclic magnetic fields can be produced by two basic mechanisms (see Parker 1979 and Cattaneo, Hughes & Weiss 1991): dynamo action, where both the poloidal and toroidal components of the field reverse after each half-cycle; and oscillation, where a reversing toroidal field is generated by the shearing of a non-reversing poloidal component.

In this paper we continue our investigation (see Sarna, Muslimov & Yerli 1997; hereafter Paper I) of dynamo operation in the mass-losing companion of Algol-type bianries. One of the ultimate goals of our study is to test dynamo theories in situations extremely different (see Muslimov & Sarna 1996) from those in single main-sequence stars. Another possible application of our analysis that we shall addreess in this paper is to trace magnetic activity (and associated X-ray activity) of a donor star in Algol-type binaries. This should advance our understanding of a causal connection between the systematic parameters and degree of the magnetic activity in the donor star. For example, it is very important to understand functioning of the magnetic braking and occurrence of magnetic cycles in the donor star during its binary evolution. For our purpose we have selected systems with the measured X-ray fluxes [e.g., by *Einstein* (White et al. 1980, White & Marshall 1983) and *ROSAT* (Welty & Ramsey 1995; Singh, Drake & White 1995, 1996)]. These systems seem to represent the snapshots of a typical Algol-type binary at different phases of mass transfer, and therefore we believe that they are the best candidates for a study of the magnetic braking and cyclic magnetic dynamos in Algol-type binaries. To illustrate this, we have calculated evolutionary sequences which fit the observed physical and orbital parameters of the systems β Per and U Sge. These particular systems were chosen because U Sge exhibits case AB non-conservative mass transfer (Sarna & De Greve 1994), whereas β Per exhibits early case B non-conservative mass transfer (Sarna 1993). In addition, these systems have well-known orbital and (present) stellar parameters. We can therefore calculate the

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'initial' systemic parameters back to the moment when the systems were detached. Then, given the 'initial' and 'final' (present) parameters, we can reproduce the plausible evolutionary sequences for the systems by modelling the magnetic braking of the donor star.

We shall demonstrate that the evolutions of U Sge and β Per can be self-consistently explained in terms of evolutionary changes in the magnetic braking associated with an increase and a subsequent decrease in the efficiency of dynamo action in the mass-losing star (cf. Muslimov & Sarna 1996; Paper I) during its binary evolution. We shall also discuss possible implication of cyclic dynamos to magnetic activity, which presumably takes place in some Algol-type binaries during the late phases of mass transfer.

In this paper an initially more massive star (the loser/donor) will be referred to as a *secondary* with mass M_2, and an initially less massive star (the gainer/mass-accreting star) will be referred to as a *primary* with mass M_1. This definition meets the observers' tradition for the observed semi-detached systems.

The paper is organized as follows. In Section 2 we briefly outline the available X-ray observations of Algol-type systmes. We classify all Algol-type binaries into four major groups according to their most likely status in terms of their binary evoluton and stellar evolution of the mass-losing component. In Section 3 we describe our numerical code and evolutionary calculations. We discuss our basic assumptions and method of calculation in Section 3.1. In Section 3.2 we discuss our treatment of magnetic braking, which is important mechanism for the loss of orbital angular momentum and mass from the binary in our evolutionary calculations. In Section 4 we present the main results of our study. In Section 4.1 we discuss the calculated evolutionary sequences for β Per and U Sge, the prototypes of stars from Groups 1 and 3 respectively. In Section 4.2 we discuss the plausible regimes of dynamo operation in the donor stars that are components of Algol-type systems, and suggest that the observed X-ray activity in these systems may be remarkably correlated with these regimes. In Section 5 we discuss our main results and summarize our conclusions.

2 X-RAY OBSERVATIONS OF ALGOL-TYPE BINARIES

Algol-type bianries, usually referred to as semidetached binary systems (or cool semidetached systems, according to, e.g., Popper 1989), where one of the components fills its Roche lobe and transfers material to its dwarf (luminosity class V) or subgiant (class IV–III) companion. In this paper we shall also use the term 'well-determined system' to distinguish double spectroscopic binaries for which photometric light curves (in at least two colours) are available.

In Table 1 we summarize the available data on the X-ray (Welty & Ramsey 1995; White & Marshall 1983; Singh et al. 1995, 1996) and radio emission (Mutel et al. 1985; Slee et al. 1987; Umana, Catalano & Rodono 1991; Strassmeier et al. 1993; Güdel & Elias II 1996) in well-studied Algol-type binaries. The entires '–' mean the absence of (published) data. The stellar and orbital parmeters for these systems are also listed in Table 1 (see Batten, Fletcher & MacCarthy 1989; Popper 1989; Strassmeier et al. 1993; Maxted & Hilditch 1996 and Sarna & De Greve 1996 for details). We have selected the 23 Algol-type binaries from the three main published sources of data: White & Marshall (1983), Welty & Ramsey (1995) and Singh et al. (1996). We must note that the values of X-ray flux given by Singh et al. (1996) are systematically higher than those presented by White & Marshall (1983). This systematic difference is apparently a result of the following two effects. First, the observations performed with the solid-state spectrometer abroad the *Einstein* satellite (White & Marshall 1983) were subject to systematic errors in calibration of the detector caused by the accumulation of ice on the surface of the spectrometer. Second, Singh et al. (1996) have used the count rate to flux conversion factor as large as twice that used by Welty & Ramsey (1995). Singh et al. claimed that the larger conversion factor was needed to account for the element abundances in the plasma models used for the analysis of the spectra.

We propose to sort the Algol-type systems into four main groups depending on their evolutionary status:

Group 1: Algol-type binaries in an active phase of mass transfer.

Group 2: Algol-type binaries in the end of mass transfer.

Group 3: Massive-Algol-type binaries where both stars seem to have radiative envelopes.

Group 4: Algol-type binaries where both components are (sub) giants with a thick convective envelope (also classified as RS CVns).

In this paper we would like to draw reader's attention to the fact that X-ray activity of the binaries under discussion correlates remarkably well with their evolutionary status (see Table 1, Groups 1–4). For example, for Group 1 the mean value of the X-ray luminosity is approximately 10^{31} erg s^{-1}. For most systems from Groups 2 and 3 only the upper limits for the X-ray luminosity are available, and U Cep is perhaps the most luminous system among stars of Groups 1–3. Table 1 shows that the X-ray luminosities of stars (except U Cep) from Groups 2 and 3 tend to be lower than the average luminosity of Group 1. It is generally believed that the radio activity is also related to the convection zone and the presence of large-scale surface magnetic fields. In systems containing magnetically active components with a developed convection zone (se, e.g., Olson 1981 and Richards & Albright 1993), the radio flux is produced by synchrotron emission (in Table 1 these systems are in Groups 1, 2 and 4). For more massive systems (Group 3), like β Lyr or U Cep, that are in a fast phase of mass transfer, the radio flux is produced by a thermal emission from the extended circumbinary matter. However, our analysis does no allow us to track down a correlation between the observed radio flux and evolutionary status of the systems. To find such a correlation (if it exists) we would need to know the details of the mechanism of radio emission and the physical conditions in the emitting regions. In contrast to the X-ray emission, for which we can justifiably use the overall efficiency for the transformation of convection energy flux into the X-ray flux (see Section 4.1 for details), the radio emission depends on the strength of the local magnetic field which implies yet another unknown parameter characterizing, e.g., the inhomogeneity of a coronal magnetic pattern. Note that the differences between the

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Table 1. Properties of Algol-type binaries.

Name	X–ray luminosity		Radio flux		Orbital parameters			Sp. Type
	White & Marshall	Singh et al.		Ref.	M_1	M_2	Period	
	[$\times 10^{30}$ ergs s^{-1}]		[mJy]		[$M_\odot$]		[days]	
Group 1								
RZ Cas	–	11.5	3.25	3	2.21	0.73	1.195	A3V/K0
U CrB	–	16.4	0.2±0.03	5	4.8	1.40	3.452	B6V/F8III
TW Dra	6.3	7.9	3.9	3	1.57	0.73	2.807	A5V/K0
β Per	4–7[10]^c	7.4	20–25	1	3.7	0.81	2.867	B8V/K2IV
TX UMa	–	7.0	0.19±0.03	5	3.2	0.96	3.063	B8V/G0III-IV
Group 2								
RY Aqr	2.0	–	5.4^a	2	1.26	0.26	1.967	A8V/K1
S Cnc	$< 1.6^a$	5.9^a	10.5±3.1	2	2.33	0.175	9.485	A0V/K0-1
AS Eri	1.3	–	< 0.09	3	1.92	0.207	2.664	A3V/K0
RY Gem	1–7[20]^c	–	4.0±1.1	2	1.9	0.31	9.301	A0IV-V/K2
TT Hya	–	0.7^a	8.1^a	2	2.3	0.42	6.953	B9.5V
XZ Sgr	–	1.8^a	6.7±1.8	2	1.9	0.31	3.269	A3V/K
Group 3								
U Cep	7.9	18.6	–		4.43	2.92	2.493	B7V/G8III-IV
δ Lib	–	5.0	64.4±7.1	2	4.9	1.70	2.327	A0-B9.5V/G
U Sge	$< 5.^b$	–	6.6^a	2	4.45	1.65	3.381	B8IV-V/G2-4III-IV
λ Tau	–	0.04^a	6.6^a	2	7.18	1.89	3.954	B3V/A3-
RS Vul	2.0	2.5^a	–		6.95	1.76	4.478	B5V/G0IV
	Welty & Ramsey							
Group 4								
AD Cap	25.0	25.0	4.8±1.3	3	1.06	0.56	2.960	G5-8IV-V/G5
RZ Cnc	10.58	17.5	< 0.27	4	3.2	0.54	21.643	K1III/K3-4III
BL CVn	4.52	7.1	< 0.16	4	0.69	0.68	18.692	G-KIV/K0III
V1764 Cyg	7.52	12.0	$< 0.51^d$	4	1.3	1.5	39.878	F/K1III
RT Lac	4.16	6.6	0.76±0.03	4	0.78	1.66	5.074	G5:/G9IV
RV Lib	11.5	11.5	43.9±4.6	3	2.36	0.43	10.722	G8IV/K3IV
AR Mon	23.6	37.3	4.8^a	3	2.7	0.80	21.208	G8III/K2-3III

[a] 3σ upper limit.

[b] Source was at the edge of the field of view.

[c] The value in bracket is the X-ray flux a flare.

[d] Possible nearby radio source.

References: 1. Mutel et al. (1985) at 5 GHz (6 cm). 2. Slee et al. (1987) at 8.4 GHz (3.6 cm). 3. Umana, Catalano & Rodono (1991) a 5 GHz (6 cm). 4. Strassmeier et al. (1993) at 5 GHz (6 cm). 5. Güdel & Elias II (1996) at 8.4 GHz (3.6 cm).

average radio fluxes for each of Groups 1–4 are not significant, so that these groups are indistinguishable in terms of the observed radio fluxes, even though the flux variations within an individual group are substantial.

With this paper we begin analysing the X-ray activity of mass-losing stars, components of Algol-type systems, which is presumably driven by stellar convection via dynamo action and generation of a hot corona. It is generally believed that convective motions generate acoustic and MHD waves that propagate upward and heat the chromosphere and corona. The flux of the wave energy may contribute significantly to the thermal balance of the chromosphere and corona. Thus the flux of the coronal X-ray emission may be of order of the input wave-energy flux. Strong stellar X-ray emission is usually explained in terms of thermal emission from a hot atmospheric plasma ($\sim 10^6$–$10^{7.5}$ K). However, in some Algol-type binaries (Sarna 1992) and semidetatched RS CVn systems (Welty & Ramsey 1995) the X-ray emission might be generated as a result of an interaction between the infalling stream of accreting matter and the star. In most Algol-type binaries the mass transfer occurs on a thermal time-scale, and the rate of mass accretion reaches 10^{-5}–10^{-4} $M_\odot$ yr^{-1}. The accretion on to the secondary component is not spherically symmetric (U Cep: Kondo, McCluskey & Stancel 1979), and the stream produces a hot region on one side of the star. The 'kinetic temperature' of a stream associated with its bulk motion is typically $\sim 10^7$ K (see, e.g., Webbink 1976). The 'accretion energy' may also be released as a non-thermal UV or X-ray emission from the shock front.

3 METHOD OF CALCULATION

3.1 The evolutionary code

In our calculations we assume that semidetached evolution is non-conservative, i.e., the total mass and angular momentum of the system are not conserved. The formalism we use in our treatment of the angular momentum loss from a system is as follows (Muslimov & Sarna 1993; Sarna & De

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Greve 1994, 1996). We introduce the parameter f_1 characterizing the loss of mass from a binary system and defined by the relations

$$\dot{M} = \dot{M}_2 f_1, \qquad \dot{M}_1 = -\dot{M}_2(1 - f_1), \tag{1}$$

where $\dot{M}$ is the rate of mass-loss from the system, $\dot{M}_2$ is the rate of Roche lobe overflow by the secondary, and $\dot{M}_1$ is the accretion rate on to the primary. The matter leaving a system will carry off its intrinsic angular momentum on a timescale given by

$$\frac{\mathrm{d}\ln J}{\mathrm{d}t} = f_2 \frac{M_1 \dot{M}}{M_2(M_1 + M_2)}\ \mathrm{yr}^{-1}, \tag{2}$$

where M_1 and M_2 are the masses of the primary and the secondary, respectively. Here we have introduced the additional parameter f_2, which describes the efficiency of the orbital angular momentum loss from a system. Note that the parameter f_2 in the above equation is chose so as to allow the orbital period to vary as a single-valued function of the current masses of the components (for a given initial mass of a secondary $M_{2\mathrm{i}}$, initial mass ratio $q_\mathrm{i} = M_{2\mathrm{i}}/M_{1\mathrm{i}}$, and initial orbital period P_i), and is therefore independent of the variation of the mass-loss rate during the evolution.

From the above equations and the standard orbit theory we find that

$$f_2 = \frac{\Delta \log P - \Delta \log(M_1 + M_2) + 3\Delta \log(M_1 M_2)}{3[f_1 \Delta \log M_2 - \Delta \log(M_1 + M_2)]}, \tag{3}$$

where Δ means a change in systemic parameters between the observed and initial stages. The above equation shows that, given the present orbital period and mass ratio of a system, we can infer the initial parameters of a system for appropriate values of f_1 and f_2.

We assume also that a donor star possessing a convective envelope experiences magnetic braking and, as a consequence of this, the system loses its orbital angular momentum. For the systems with very short orbital periods, in the final stages of evolution, we also take into account the loss of orbital angular momentum due to the emission of gravitational radiation (Landau & Lifshitz 1971).

The models of the stars filling their Roche lobes were computed using a standard stellar evolution code based on the Henyey-type code of Paczyński (1970), which has been adapted for low-mass stars. Convection is treated with the mixing-length algorithm proposed by Paczyński (1969). We solve the problem of radiative transport by employing the opacity tables of Iglesias, Rogers & Wilson (1992). Where the Iglesias et al. 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 that is provided in Huebner et al. the opacity tables has been included in the other tables as well. Finally, we assume a Population I chemical composition for the mass-losing component ($X = 0.7$; $Z = 0.03$).

3.2 Magnetic braking

In our evolutionary calculations the rate of loss of orbital angular momentum due to magnetic braking of the donor star is usually calibrated by the parameter λ (parameter f using the notation of Verbunt & Zwaan 1981; see also Iben & Tutukov 1984) ranging from ~ 0.73 (Skumanich 1972) to ~ 1.78 (Smith 1979).

The standard expression for the orbital angular momentum loss due to the stellar magnetic braking (Mestel 1968; Mestel & Spruit 1987) reads

$$\left(\frac{\mathrm{d}\ln J}{\mathrm{d}t}\right)_{\mathrm{MB}} = -3 \times 10^{-7} \frac{1}{\lambda^2} \frac{m^2 r_\mathrm{c}^4}{m_1 a^5}\ \mathrm{yr}^{-1}. \tag{4}$$

where $J[= (M_1 M_2/M) A^2 \Omega_\mathrm{orb}]$ is the orbital angular momentum of the system, m_1 and m_2 are the masses (in solar units) of the main-sequence star and the loser respectively ($m = m_1 + m_2$), and r_c and a are the radius of the companion and the orbital separation (both in solar units) respectively.

In this paper we calculate evolutionary sequences with allowance for dynamo action in the donar star. This means that in our calculations, instead of using a standard λ, we exploit an explicit expression for it in terms of stellar and dynamo-related parameters (see Muslimov & Sarna 1996 and Paper I for details):

$$\lambda = \lambda_0 \frac{1}{H_{\mathrm{p}9}^2} \frac{r_\mathrm{c}^2}{r_{\mathrm{b}9}} \left(\frac{m_2}{\rho_\mathrm{b}}\right)^{1/2} T_6^{1/4} N_\mathrm{D}^{1/2}, \tag{5}$$

where $\lambda_0(\sim 0.1\text{–}0.5)$ is the normalization value, $r_{\mathrm{b}9} \equiv r_\mathrm{b}/10^9$ cm, $H_{\mathrm{p}9} \equiv H_\mathrm{p}/10^9$ cm, $T_6 \equiv T_\mathrm{ph}/10^6$ K, T_ph is the photospheric temperature of a donor, ρ_b is the mass density at the base of convection zone in g cm^{-3}, $N_\mathrm{D} \approx (\Omega\tau_\mathrm{con})^2$ is the dynamo number ($N_\mathrm{D} = Ro^{-2}$, where Ro is the Rossby number), Ω is the stellar angular velocity, and τ_con is the convection turnover time.

Note that stellar magnetic activity is known to be anticorrelated with the Rossby number (see, e.g., Weiss 1994 for a review): the level of stellar magnetic activity (deduced, for example from measurements of Ca$^+$ emission from stars which are known as good indicators of magnetic stellar activity) increases as the Rossby number decreases. Although a simple-minded extrapolation of this empirical relationship on to the rapidly rotating low-mass stars in binaries is by no means warranted, our calculations may sensibly indicate that the same general tendency holds (see also the discussion at the end of the next paragraph).

Equation (5) shows that the efficiency of magnetic braking is rather sensitively determined by the characteristic density and pressure scaleheight of the layer in which the dynamo action is thought to occur (see Muslimov & Sarna 1996 and Paper I). For example, in the case of evolutionary sequence calculated for an initially main-sequence star, the efficiency of magnetic braking increases during the evolution, mostly because of an increase in the matter density of of the 'dynamo-operating' layer. In contrast, in the cases of evolutionary sequences calculated for stars with small helium cores, the efficiency of magnetic braking during the very late stages of evolution dramatically decreases, because the dynamo-operating layer tends toward lower mass densities. In other words, as our calculations show (Muslimov & Sarna 1996; Paper I), for companions evolving from a main-sequence star, the kinetic energy of convective motions near the base of a convection zone decreases during the evolu-

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tion, but only by less than a factor of ~ 10. On the contrary, for companions evolving from stars with small helium cores, the energy reservoir for dynamo operation is reduced during the evolution by a factor of $\sim 10^3$. In the following we shall illustrate this effect explicit.

4 MAIN RESULTS

4.1 Evolutionary sequences

We have calculated the evolutionary sequences that fit the present parameters of β Per and U Sge. The initial parameters we have used in our calculations for β Per and U Sge are presented by Sarna (1993) and Sarna & De Greve (1994) respectively.

***β* Per.** By analysing the positions of the donor and the gainer in luminosity–mass and radius–mass diagrams, we conclude that the system exhibits an early case B mass transfer with $M_{2\mathrm{i}} = 2.81$ M$_\odot$, $M_{1\mathrm{i}} = 2.50$ M$_\odot$ $P_\mathrm{i} = 1.61$ d, and the parameters $f_1 = 0.40$ and $f_2 = 1.82$ are obtained using equations (1) and (2) respectively.

U Sge. Using the same reasoning as for β Per, we conclude that $q_\mathrm{i} \simeq 1$, and that the present position of the system can be easily explained in terms of case AB mass transfer. Given the initial mass of the secondary, $M_{2\mathrm{i}} = 3.27$ M$_\odot$, for the intial mass of the primary and the initial orbital period of the system, we get 3.25 M$_\odot$ and 1.56 d respectively. Thus, using equations (1) and (2), we obtain the values $f_1 = 0.26$ and $f_2 = 0.82$.

Figs 1 and 2 display the evolution of the thickness of the convection zone for the secondary components of β Per (Figs 1a and 2a) and U Sge (Figs 1d and 2d). They show that a relatively thick convective envelope is developed at the very beginning of the semi detached phase. This means that one can expect a solar-type wind at this phase. It is interesting to note that both systems are in the same phase of a fast mass transfer, but in different phases of their magnetic activity.

β Per is in a final state of building up its thick convection zone, while U Sge is just a the beginning of forming such a zone. We may therefore suggest that dynamo action in U Sge is less efficient than in β Per, and that its X-ray activity is weaker. Figs 1(b), 2(b) and 1(c), (2c) show that a thick convection zone develops earlier for the loser in late phases of case B mass transfer (i.e., when the mass of the helium core is greater than ~ 0.25 M$_\odot$) rather than in early case B mass transfer.

We suggest that U Cep, which is in Group 3 (Table 1), has experienced a late case B mass transfer, and that at the very beginning of mass transfer the loser of the system has developed a thick convection zone. For this system the X-ray activity of the donor is likely to have resulted from its

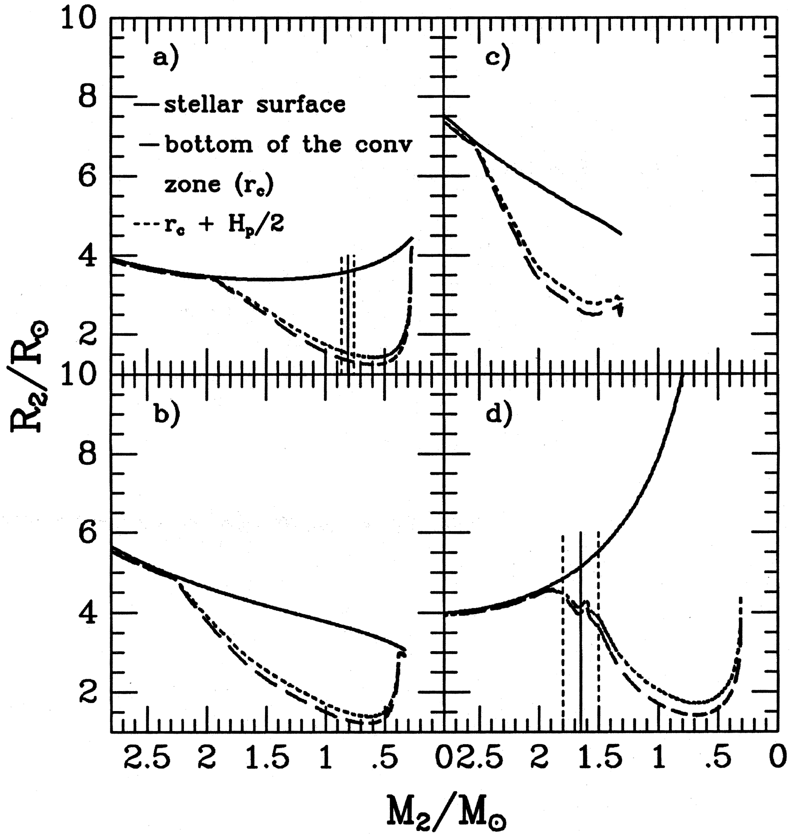

Figure 1. Thickness of the convection zone as a function of the mass of a donor star, calculated for the evolving stellar models of donor star in β Per and U Sge: (a) the evolutionary calculations are performed for the following initial parameters of β Per: $M_{2\mathrm{i}} = 2.81$ M$_\odot$, $f_1 = 0.4$, $f_2 = 1.82$ and $q_\mathrm{i} = M_{2\mathrm{i}}/M_{1\mathrm{i}} = 1.12$; (b) as in (a), but for $f_2 = 2.35$; (c) as in (a) but for $f_2 = 2.79$; (d) the evolutionary calculations for the initial parameters of U Sge: $M_{2\mathrm{i}} = 3.27$ M$_\odot$, $f_1 = 0.41$, $f_2 = 0.92$ and $q_\mathrm{i} = M_{2\mathrm{i}}/M_{1\mathrm{i}} = 1.001$. The positions of the donor for the systems β Per (a), U Sge (d) and U Cep (b and c) are marked by thin vertical solid lines. The errors in mass determination are marked by dashed vertical lines.

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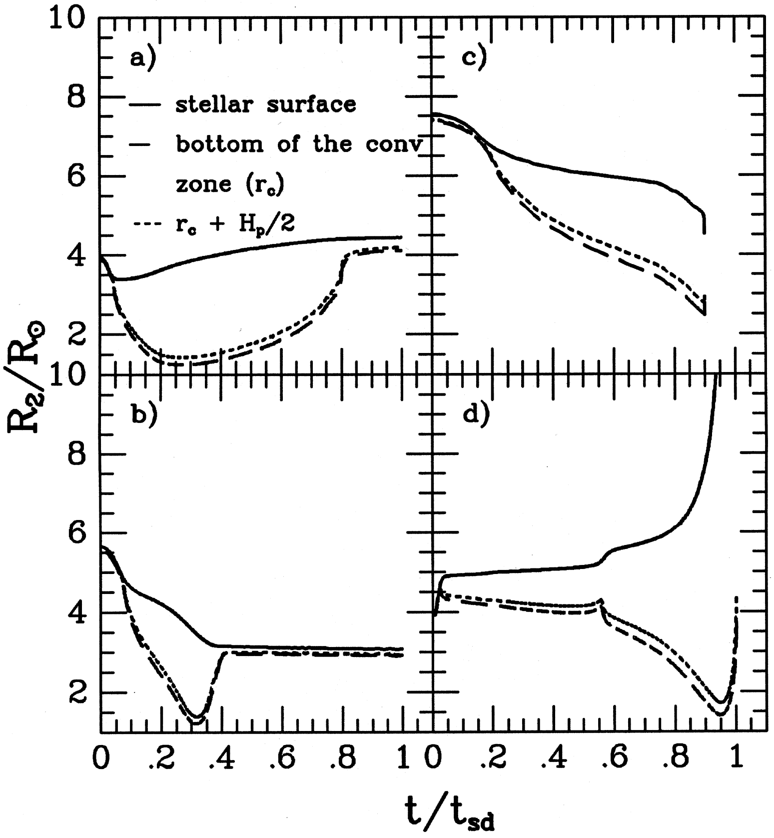

Figure 2. Thickness of the convection zone as a function of time normalized by the time-scale of semidetached evolution t_{sd}. The calculations are presented for the evolving stellar models of donor star in β Per and U Sge: (a) $t_{sd}=2\times10^7$ yr, (b) $t_{sd}=6.1\times10^6$ yr, (c) $t_{sd}=1.1\times10^6$ yr, (d) $t_{sd}=2\times10^8$ yr. Other details are the same as in Fig. 1.

enhanced magnetic activity similar to RS CVn-type stars (Group 4). Other systems from the Group 3 have evolved in case AB or early case B mass transfer, and they are at the beginning of forming a thick convection zone. The systems in Group 4 are not indicated in Fig. 1, because both components in these systems are magnetically active giants or subgiants, and are therefore indistinguishable in terms of our analysis.

4.2 Dynamo action in a mass-losing star

To approach the issue of evolutionary effects in magnetic activity of the mass-losing star we shall calculate the secular behaviour of certain critical numbers which characterize the efficiency of dynamo action within the framework of a standard α–ω dynamo (cf. Muslimov & Sarna 1996; Paper I). It is interesting that in the active subgiants, components of RS CVn binaries (Group 4), the dynamo mode may be different from that believed to be relevant to the solar-type stars (see also Group 1). For example, the non-axisymmetric dynamo (see Moss et al. 1995, and references therein) may be a reasonable possibility for these stars. Moss et el. (1995) demonstrated the existence of two stable solutions with the non-axisymmetric pattern of the large-scale magnetic field: one for moderate Taylor numbers ($N_T=4\Omega^2 d^4/\nu^2$, where Ω is the stellar angular velocity, d is the thickness of the convection zone, and ν is the kinematic viscosity produced by turbulent motions), and weak differential rotation, and another for large Taylor numbers and strong differential rotation.

The results of our calculations for the standard α–ω dynamo are summarized in Figs 3 and 4. Fig. 3 shows that the parameter λ changes substantially during the evolution of the mass-losing star in the binary. As is seen from Fig. 3(a), the efficiency of magnetic braking is high only during a certain phase of semidetached evolution – when the mass of the donor star decreases from 1.5 to 0.3–0.2 $M_\odot$. The efficiency of magnetic braking increases monotonically by a factor of 200 during the first $\sim10^6$ yr (the phase of fast mass transfer). Then, for the donor star of massof 1.4–1.25 $M_\odot$, λ decreases to a value of 1 (which corresponds to the standard implied efficiency of magnetic braking), and afterwards, during $\sim10^7$ yr (early case B) or a few $\times10^8$ yr (case AB), it gradually levels down to a value of 0.01 (which corresponds to anomalously efficient magnetic braking). Finally, during the very late stages of evolution, λ increases by more than a factor of 500. The latter means that the magnetic braking is effectively switched off when the mass of the companion has decreased to 0.3–0.2 $M_\odot$. The range of masses where magnetic braking is important depends on the initial parameters of the system. For example, if the system begins mass exchange during late case B, then this range is 2.2 to 0.5–0.4 $M_\odot$ (Fig. 3b). For early case B or case AB it is 1.5 to 0.3–0.2 $M_\odot$ (Fig. 3a).

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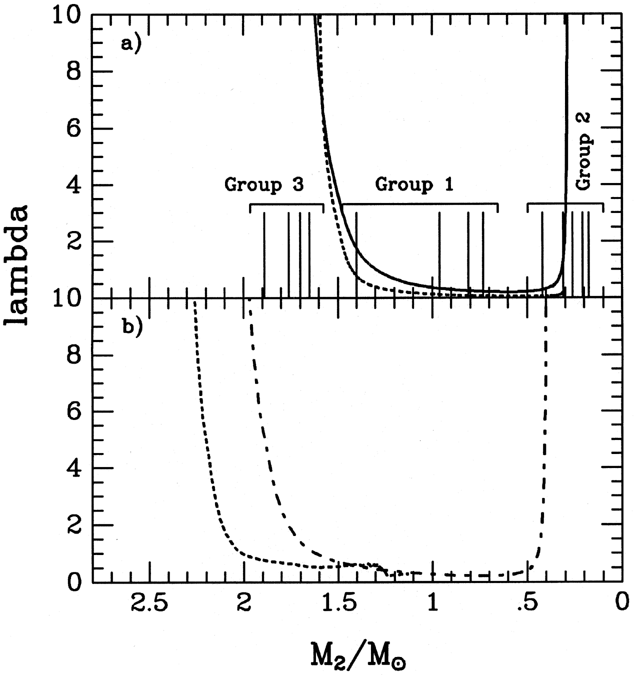

Figure 3. Calculated value of the parameter λ (see also Section 3) as a function of the mass of a donor star. Panel (a) shows the results for β Per (solid line) and U Sge (dotted line). The positions of the donor star from Groups 1–3 are marked by thin vertical solid lines. Panel (b) shows evolution of λ for the same initial parameters as for β Per, but for $f_2=2.35$ (dot-dashed line) and $f_2=2.79$ (dotted line).

In Fig. 4 we demonstrate the evolution of the Rossby number. During the fast mass-transfer phase the Rossby number decreases (see Table 1, Group 3) by a factor of 300 relative to the initial value (because of the rapid increase in the turnover time caused by the development of a thick convection zone) and then reaches a minimum level, a phase which can be associated with the enhanced magnetic activity (dynamo action) in the donor star (see Table 1, Groups 1 and 4). During the very late stages of the evolution, the Rossby number increases by a factor of 400 because of the rapid decrease (caused by effective hydrogen shell burning and by increase in orbital separation) in the thickness of the convection zone. For this phase of evolution it is natural to ssume that magnetic activity in the donor star declines (see Table 1, Group 2).

We suggest that of all the systems under analysis, only those from the Groups 1 and 4 (see Table 1) are the most favourable for the operation of a dynamo in the donor star. The systems from Group 2 or 3 are either at the beginning of forming a thick convection zone or at the end of mass transfer (where the thickness of the convection zone decreases). It is not surprising therefore that the stellar X-ray activity in Groups 1 and 4 is at a much higher level than in Groups 2 and 3. In Table 2 we have listed the systems that we believe are potential candidates for these four groups. Note that we have included the system R CMa in Group 2, even though it may be magnetically very active, but its activity is expected to be due to the primary rather than the secondary component.

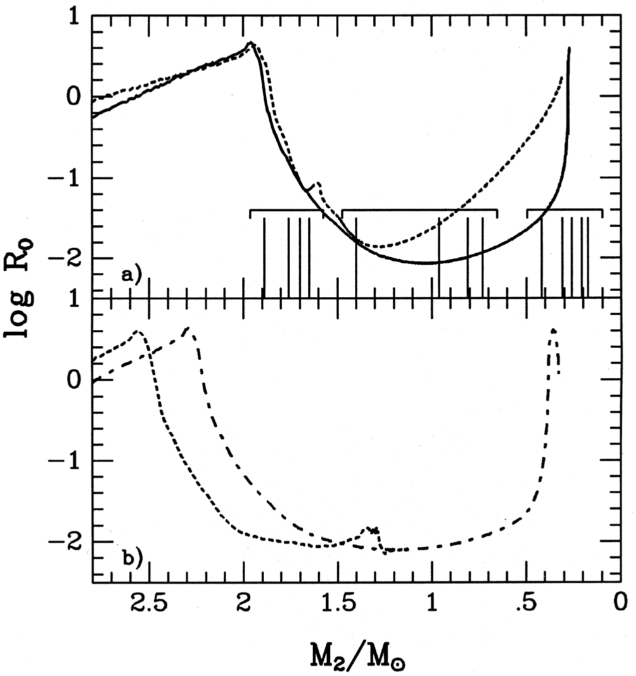

Figure 4. Calculated value of Rossby number as a function of the mass of a donor star. Other details are the same as in Fig. 3.

Table 2. Parameters of Algol-type binaries, candidates for X-ray observations.

Name	Radio flux [mJy]	Ref.	Orbital parameters M_1 [$M_\odot$]	M_2 [$M_\odot$]	Period [days]	Sp. Type
Group 1						
TV Cas	< 5	1	3.29	1.53	1.813	B9V/G5:
AF Gem	–		3.37	1.155	1.244	B9.5V/G0III-IV
AT Peg	–		2.22	1.05	1.146	A4V/G
HU Tau	–		4.43	1.14	2.056	B8V/G2
RW Tau	0.25±0.03	4	2.55	0.55	2.769	B8V/K0IV
X Tri	< 5	1	2.3	1.2	0.972	A5V/G0V
Group 2						
TW And	< 5	1	1.67	0.32	4.123	A7V/K0-1
R CMa	8.1±2.4	2	1.1	0.17	1.136	F0IV/K3IV-V
RV Oph	–		3.2	0.3	3.687	A0V/K0
DN Ori	< 0.15	4	2.65	0.18	12.966	A5V/K3-4
	0.11±0.03	4a				
RW Per	< 0.15 [0.09]	4	2.3	0.25	13.199	B9.5IV-V
	0.1±0.03	4a				
S Vel	7.5^a	2	2.0	0.30	5.934	A5V/K3-4
Group 3						
WW Cyg	0.127±0.05	4	6.2	1.9	3.318	B8V/G9:
68 Her	–		7.6	2.9	2.051	B2V/B5
TU Mon	< 0.1	4	12.7	2.7	5.049	B5V/A9
V Pup	–		17.0	9.0	1.454	B1V/B2
V356 Sgr	–		12.1	4.7	8.897	B4V/A2II
Z Vul	–		5.4	2.3	2.455	B3V/A1-2
Group 4						
RX Cas	< 0.14	4	2.3	0.69	32.327	gA5/gG3
	< 0.08	4a				
UZ Cyg	< 0.11	4	3.6	0.25	31.306	A3/K4
AW Peg	< 5	1	2.0	0.32	10.623	A3-5/G3-4

[a] 3σ upper limit.

References: 1. Altenhoff et al. (1976) at 10.69 GHz (2.8 cm). 2. Slee et al. (1987) at 8.4 GHz (3.6 cm). 3. Umana, Catalano & Rodono (1991) at 5 GHz (6 cm). 4. Güdel & ELias II (1996) at 8.4 GHz (3.6 cm). 4a. Güdel & Elias II (1996) at 5 GHz (6 cm).

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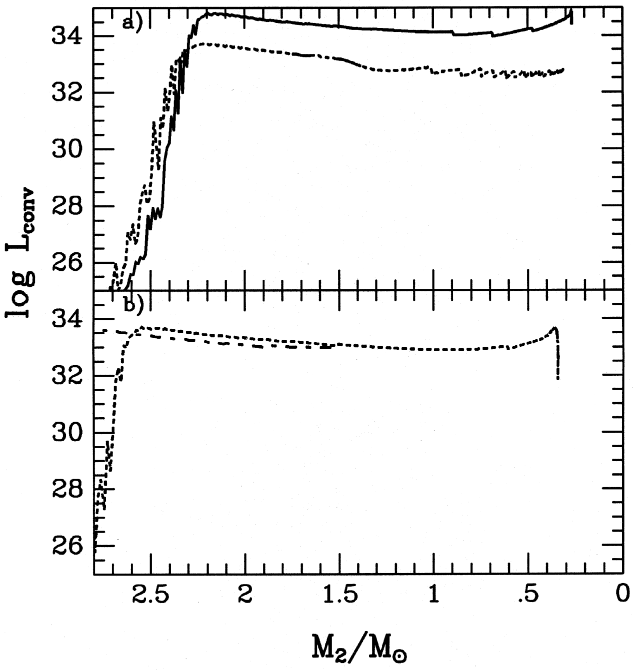

Figure 5. Convective luminosity calculated at the outermost boundary of a convective zone as a function of the mass of a donor star. Panel (a) shows the convective luminosity for a star evolving in a binary like β Per (solid line) and U Sge (doted line). Panel (b) shows the convective luminosity for a star evolving in a binary with initial systematic parameters as for β Per, but for $f_2=2.35$ (dot-dashed line) and $f_2=2.79$ (dotted line).

In Fig. 5 we present evolution of the convective luminosity (calculated at the upper boundary of a convection zone) for a star undergoing the same evolutionary tracks as in Figs 3 and 4.

Fig. 5 shows that the convective luminosity increases dramatically as the star enters Group 1. Accordingly, the flux of the wave energy into the chromosphere and corona may increase dramatically for stars of this group. Thus for Group 1 we may estimate the efficiency of a transformation of the convective flux into the X-ray flux as ~ 0.1 per cent. It is very interesting that the X-ray luminosity of stars from Group 1 is essentially of the same order of magnitude, which may suggest that the efficiency of a transformation of the convective flux into the X-ray flux in these stars remains nearly constant up to the very last stages of evolution. However, as Fig. 4 indicates, the Rossby number increases at the very late stages of evolution by at least two orders of magnitude. This fact is very crucial for any dynamo, and it may determine a steep turn-off of the coronal X-ray emission, which is probably observed in stars of Group 2. The large dispersion of the X-ray fluxes characteristic of Groups 2 and 3 seems to reflect the steep evolutionary increase of the Rossby number and convective luminosity respectively.

5 DISCUSSION AND CONCLUSIONS

In this paper we have calculated evolutionary sequences for the donor stars in Algol-type binaries, taking into account an approximate expression for the loss of orbital angular momentum due to magnetic stellar braking. This expression is based on a relation between the equipartition value for the toroidal magnetic field generated near the base of convection zone and the surface value of the large-scale poloidal magnetic field. The former depends strongly on physical stellar parameters such as the thickness of the convection zone, stellar mass, etc., which change significantly during evolution of a system, while the latter determines the magnetic braking.

As a result of our analysis, we propose to sort all Algol-type binaries into four groups. During its binary evolution, the mass-losing star goes through different stages in which it has different internal structures. One of the key physical parameters that characterizes the evolutionary stage of the donor and eventually determines its X-ray activity is the thickness of its convection zone. We have suggested a classification of the Algol-type binaries according to whether the stellar parameters of the donor favour dynamo operation or not. Our classification implies that the observed X-ray luminosity of the system should be correlated with an evolutionary stage of the donor star.

(i) Group 1. The Algol-type binaries that transfer matter on a thermal time-scale have a thick convection zone, and therefore one can expect that the dynamo operates efficiently in these stars. The occurrence of the hot corona and enhanced X-ray stellar activity should be characteristric of these stars.

(ii) Group 2. The Algol-type binaries in the end of their mass transfer (mass transfer occurs on the nuclear time-scale). The dynamo operates inefficiently in the donor star, and the stellar X-ray luminosity is smaller than that for Group 1.

(iii) Group 3. Massive Algol-type binaries (excluding the system U Cep) with the stellar components possessing radiative envelopes.

(iv) Group 4. The Algol-type binaries (also classified as RS CNns) where both components are (sub)giants. In these stars showing relatively high X-ray activity the operation of the non-axisymmetric dynamo may be most favoured (Moss et al. 1995).

Using our evolution-based criterion for the magnetic activity of Algol-type binaries, we have listed the candidate systems for the X-ray observations. If the concept of dynamo is generally correct, then our scheme of classification is robust and can be used in future X-ray surveys of Algol-type binaries. Moreover, we suggest that the stars within maximum X-ray activity form a rather homogeneous subpopulation for which we can predict the observed X-ray fluxes, provided that the latter are due to the coronal emission.

We can also conclude from our study that if any dynamo producing large-scale magnetic fields operate on the secondary component (with a thick convection zone) of an Algol-type binary, then this dynamo should be anomalously efficient (see also Muslimov & Sarna 1996 and Paper I). The preliminary analysis of the O − C (observation − calculation) diagram (Kreiner, private communication) shows that for Group 1 the quasi-periodic changes with a period of several years as well as secular ($\sim$ a few × 100 yr) variability occur. For Group 2 we do not find detectable orbital period changes. We plan to analyse these variabilities in more detail in the future.

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The challenge to the theorists is to address the issue of dynamo operation at extremely high dynamo numbers, to analyse a possibility of cyclic dynamos in a more quantitative way, and to attempt to explain the observed variety of quasi-periodic and periodic changes in Algol-type systems that are presumably associated with some sort of magnetic activity in component stars. This and our previous paper are devoted primarily to the investigation of the existence of intrinsic correlation between the stellar evolution and X-ray activity (e.g., via dynamo operation) in stars that are components of Algol-type bianries. In summary, we have reached the following conclusions.

(i) There is a remarkable correlation between the evolutionary status and X-ray activity in stars that are components of Algol-type binaries.

(ii) In donor stars, components of β Per-like systems, the conditions are most favourable for the dynamo operation.

(iii) The estimated efficiency of a transformation of the convective flux into the X-ray flux in these stars is ~ 0.1 per cent, and the corresponding X-ray luminosity is expected to be $\sim 10^{31}$ erg s^{-1}.

(iv) The stars in RS CVn-like systems may experience a dynamo different from that for solar-type stars, and this dynamo may be dominated by the non-axisymmetric mode (see Moss et al. 1995 for details).

(v) The sysems we expect to have enhanced X-ray luminosities [$\sim(0.5\text{–}1) \times 10^{31}$ erg s^{-1}] are TV Cas, AF Gem, AT Peg, HU Tau, RW Tau and X Tri.

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