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Mass Transfer, and Effects of Magnetic Fields on the Mass Transfer in Close Binary System

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1. Introduction

The gravitational potential of a binary system is described by the Roche model where each star dominates the gravitational potential inside regions called Roche lobes.The two Roche lobes meet at the inner Lagrange point along the joining of the two stars. Figure 1 shows equipotential surfaces in the orbital plane for a binary system. As may be seen from Fig. 1, there are five equilibrium points(i.e. $\nabla\phi = 0$) three of which i.e., L_1, L_2, L_3,are along the line centers. Two are peripheral to the masses and lie as the critical points along equipotentials that envelope both stars. two other points ,i.e., L_4, L_5 lie opposite to each other, perpendicular to the line of centers. These are quasi-equilibrium points for which local orbits are possible because of coriolis acceleration. If either star fills its Roche lobe, matter will stream from the Roche lobe filling star through the inner Lagrange point to the other star in a process known as Roche lobe overflow(RLOF). This actually occurs before the photosphere reaches the Roche lobe radius in the absence of magnetic fields or other constrains on the mass flow. This mass transfer affects both the evolution of the components of the binary as well as the binary properties such as orbital period and eccentricity. Roche lobe overflow can be triggered by the evolution of the binary properties or by evolution of the component stars. On the one hand, the orbital separation of the binary can change so that the Roche lobe can shrink to within the surface of one of the stars. On the other hand, stellar evolution may eventually cause one of the stars to expand to fill its Roche lobe. When both stars in the binary are main-sequence stars, the latter process is more common. Since the more massive star will evolve first, it will be the first to expand and fill its Roche lobe. At this stage, the mass exchange can be conservative (no mass is lost from the binary) or non-conservative (mass is lost). Depending on the details of the mass exchange and the evolutionary stage of the mass-losing star there are several outcomes that will lead to formation of a relativistic binary. The primary star can lose its envelope, revealing its degenerate core as either a helium, carbon-oxygen, or oxygen-neon white dwarf, it can explode as a supernova, leaving behind a neutron star or a black hole, or it can simply lose mass to the secondary so that they change roles. Barring disruption of the binary, its evolution will then continue. In most outcomes, the secondary is now the more massive of the two stars and it may evolve off the main sequence to fill its Roche lobe. The secondary can then initiate mass transfer or mass loss with the result that the secondary also can become a white dwarf (WD), neutron star (NS), or black hole (BH). The relativistic binaries that result from this process fall into a number of observable categories. A WD-MS or WD-WD binary may eventually become a cataclysmic variable once the white dwarf begins to accrete material from its companion. If the companion is a Main Sequence star RLOF can
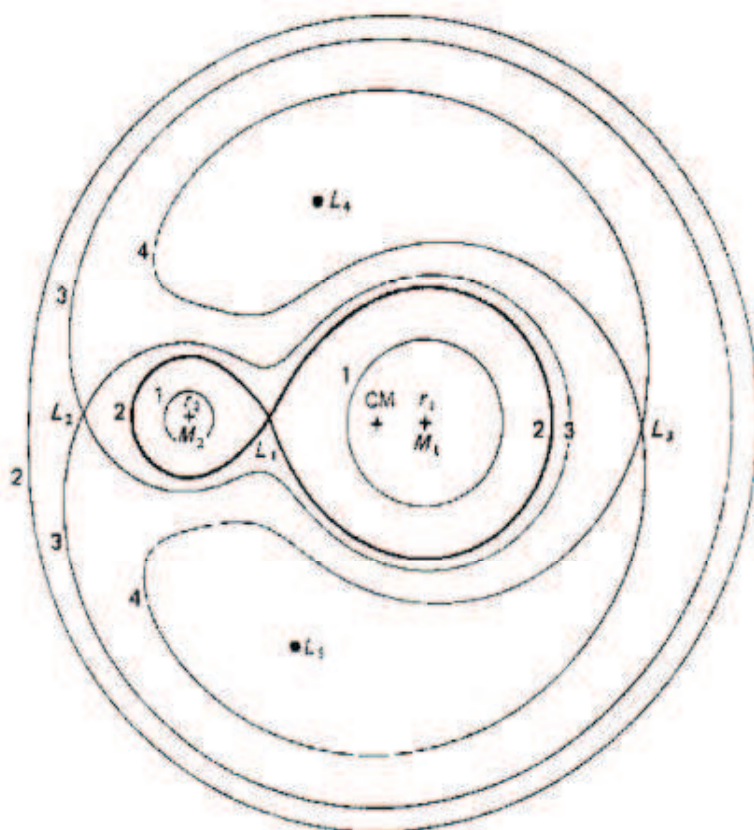
Fig. 1. Roche surface for q = 0.4. The Lagrangian points are indicated

be triggered by evolution of the companion. If the companion is another white dwarf, then RLOF is triggered by the gradual shrinking of the orbit through the emission of gravitational radiation. WD-WD cataclysmic variables are also known as AM CVn stars. If the total mass of the WD-WD binary is above the Chandrasekhar mass, the system may be a progenitor to a type I supernova. The orbit of a NS-MS or NS-WD binary will shrink due to the emission of gravitational radiation. At the onset of RLOF, the binary will become either a low-mass X-ray binary(if the donor star is a WD or MS with $M_1 \leq 2M_\odot$), or a high-mass X-ray binary(if the donor is a more massive main-sequence star).These objects may further evolve to become millisecond pulsars if the NS is spun up during the X-ray binary phase[1]. A comprehensive table of close binary types that can be observed in electromagnetic radiation can be found in Hilditch (2001). The type of binary that emerges depends upon the orbital separation and the masses of the component stars. During the evolution of a $10M_\odot$ star, the radius will slowly increase by a factor of about two as the star progresses from zero age main sequence to terminal age main sequence. The radius will then increase by about another factor of 50 as the star transitions to the red giant phase, and an additional factor of 10 during the transition to the red supergiant phase. These last two increases in size occur very quickly compared to the slow increase during the main-sequence evolution of the star. Mass transfer can be divided into three cases see (Thomas 1977) related to the timing of the onset of RLOF.

Case A: If the orbital separation is small enough (usually a few days), the star can fill its Roche lobe during its slow expansion through the main-sequence phase while still burning hydrogen in its core.

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[1]See the website, http://www.livingreviews.org

Case B: If the orbital period is less than about 100 days, but longer than a few days, the star will fill its Roche lobe during the rapid expansion to a red giant with a helium core. If the helium core ignites during this phase and the transfer is interrupted, the mass transfer is case B.

Case C: If the orbital period is above 100 days, the star can evolve to the red supergiant phase before it fills its Roche lobe. In this case, the star may have a CO or ONe core.

Case A mass transfer occurs during the slow growth, case B during the first rapid expansion, and case C during the final expansion phase. The nature of the remnant depends upon the state of the primary during the onset of RLOF and the orbital properties of the resultant binary depend upon the details of the mass transfer.

Wood (1950) studied period variations of binaries and suggested that mass ejections could be a cause of period change. Huang (1963) revised the problem of mass transfer in binary systems, he modified the Jeans(1924-1925) mode of mass ejection, through suggesting two modes of mass transfer i.e., slow and intermediate modes, in each case he was able to derive the following equations:

$$\frac{\Delta P}{P} = -3\left(\frac{M_2 - M_1}{M_2}\right)\frac{\Delta M_1}{M_1} + \frac{3e\Delta e}{1 - e^2} \qquad for\ slow\ mode \qquad (1)$$

$$\frac{\Delta P}{P} = (1 + 3\gamma_2)\left(\frac{M_2 + M_1}{M_1 + M_2}\right) - 3\frac{\Delta M_1}{M_1} + \frac{\Delta M_2}{M_2} + \frac{3e\Delta e}{1 - e^2} \qquad for\ intermediate\ mode \qquad (2)$$

Where

$$\gamma_2 = \frac{(M_1 + M_2)^2}{M_1 M_2}\left[\frac{a_e}{a(1 - e^2)}\right]^{1/2}$$

P, denotes the orbital period, $M_i s$, the masses of the components, e, eccentricity, a, semi-major axis, and Δ implies the variations of respective parameters. A true review of mass and angular momentum transfer and their consequences on the evolution of binary stars may be find by Thomas (1977).

2. Conservative mass transfer

When no ejected matter leaves a binary system, the mass transfer is said to be conservative. During consevative mass transfer, the orbital elements of the binary can change due to transfer of angular momentum from one star to the companion. Consider a system with a totat mass $M = M_1 + M_2$, semi-major axis, a, eccentricty, e, and the total orbital angular momentum, J,

$$J = M_1 M_2 \sqrt{\frac{Ga(1 - e^2)}{M_1 + M_2}} \qquad (3)$$

will also be conserved, where G, is universal grvitational constant. Hence: $\dot{J} = 0, \dot{M} = 0$ and $\dot{M_1} = -\dot{M_2}$. And We may also write

$$a = c^2 (M_1 M_2)^{-2} J^2 \qquad (4)$$

Where:

$$c = \sqrt{\frac{M}{G(1 - e^2)}}$$

, c is a constant

Differentiating eq. 3 yields

$$\frac{\dot{a}}{a} = 2\frac{\dot{J}}{J} - 2\frac{\dot{M}_1}{M_1} - 2\frac{\dot{M}_2}{M_2} + \frac{\dot{M}}{M} \tag{5}$$

Using the requirements for conservative mass transfer (mentioned just after the eq. 3) in eq. 5 we get

$$\frac{\dot{a}}{a} = 2\dot{M}_1 \left(\frac{M_2 - M_1}{M_1 M_2}\right) \tag{6}$$

If M_1 is the mass losing star $\dot{M}_1$ will be negative, therefore we conclude that if the mass donor star is more massive, then the orbit will shrink and hence period decreases. But if the mass donor is less massive than the accretor component then orbit will be widened and period increases.

By using the Kepler's third law ($\frac{P^2}{a^3} = \frac{4\pi^2}{GM}$) in eq. 6, the period variation with time $\dot{P}$ due to mass transfer can be written as,

$$\dot{P} = \frac{3\dot{M}_1(M_1 - M_2)}{M_1 M_2} P \tag{7}$$

Where P, is the orbital period.

3. Non conservative mass transfer

In case of non conservative mass transfer both mass and angular momentum can be removed from the system. Following Demircan et al. (2006) Orbital Angular Momentum (OAM) of a two body system is given by

$$J = \left(\frac{M_1 M_2}{M_1 + M_2}\right) a^2 \Omega = \left(\frac{q}{(1+q)^2}\right) M a^2 \Omega \tag{8}$$

Where,

$$\left(\frac{M_1 M_2}{M_1 + M_2}\right) a^2 = I$$

is moment of Inertia and $\Omega = \frac{2\pi}{P}$ is angular speed, P, is orbital period and $M = M_1 + M_2$, $q = \frac{M_2}{M_1}$ are total mass and mass ratio, respectively. If we assume isotropic mass loss from the surface of the components, then,

$$\dot{J} = \left(\frac{q}{(1+q)^2}\right) \dot{M} a^2 \Omega \tag{9}$$

Since the dynamics of a two body system obey Kepler's third law therefore one expects transfer of mass would change the, a, P and M accordingly,

$$3\frac{\dot{a}}{a} + 2\frac{\dot{\Omega}}{\Omega} = \frac{\dot{M}}{M} \tag{10}$$

assume q as a constant, differentiation of equation 8 with respect to "t", will give

$$\frac{\dot{J}}{J} = \frac{\dot{M}}{M} + 2\frac{\dot{a}}{a} + \frac{\dot{\Omega}}{\Omega} \tag{11}$$

if $\frac{\dot{a}}{a}$ is substituted from equation 10 to equation 11 we get,

$$\frac{\dot{J}}{J} = \frac{5}{3}\frac{\dot{M}}{M} - \frac{1}{3}\frac{\dot{\Omega}}{\Omega} = \frac{5}{3}\frac{\dot{M}}{M} + \frac{1}{3}\frac{\dot{P}}{P} \qquad (12)$$

But substitution of $\frac{\dot{\Omega}}{\Omega}$ from 10 in to 11 will give

$$\frac{\dot{J}}{J} = \frac{3}{2}\frac{\dot{M}}{M} + \frac{1}{2}\frac{\dot{a}}{a} \qquad (13)$$

Therefore the last two equations i.e. 12 and 13, give how the loss of OAM and mass are caused the orbital period, P, and orbital radius, a, to change.
According to equations 8 and 9 the isotropic mass loss implies

$$\dot{J} = \frac{\dot{M}}{M}J \qquad (14)$$

This eq. implies that the only source of OAM loss is mass loss, which were assumed to be isotropic. Substituting $\frac{\dot{J}}{J}$ from eq 14 to 12 will give,

$$\dot{P} = -2\frac{\dot{M}}{M}P \qquad (15)$$

In this last eq. since the $\frac{\dot{P}}{P}$ is measurable observationally, therefore $\frac{\dot{M}}{M}$ can be calculated from eq. 15.
Now if we use the following eqs. taken from Stepien (1995) to calculate relative angular momentum lost from a system as,

$$J = G^{2/3}M^{5/3}\Omega^{-1/3}q(1+q)^{-2} \qquad (16)$$

$$J_{lost} = \dot{J} = -\frac{1}{3}G^{2/3}M^{5/3}\Omega^{-4/3}q(1+q)^{-2}\dot{\Omega} \qquad (17)$$

and hence the relative OAM lost only by magnetized star wind

$$\frac{J_{lost}}{J} = -\frac{1}{3}\frac{\dot{\Omega}}{\Omega} \qquad (18)$$

Where

$$\dot{\Omega} = 1.8 \times 10^{-8}(\frac{k^2(M_1R_1^2 + M_2R_2^2)(1+q)^2}{qG^{2/3}M^{5/3}})\Omega^{7/3}e^{-1.3\Omega} \qquad (19)$$

Using the value of $\frac{J_{lost}}{J}$ in eq. 14, the relative mass lost from the system can be estimated. Since eq.15 may give the total mass ejected from the system. Hence the transferred mass from one component to the other easily can be estimated.

4. Effects of magnetic fields on the mass loss and mass transfer

Now it is generally accepted among the astrophysicists that close binary systems with a cool F-K type star display enhanced magnetic activities. Short period close binaries i.e., those having an orbital period $P < 5 - 6$ days, possess the just mentioned characteristics, due to rapid rotation (Richard & Albright 1993). Many authors (see e.g., Richards 1993, 1992; Hall 1989 & Olson 1981) have discussed that the secondary and/or primary in the close binaries having a late type component show a variety of time dependent magnetic properties, which causes brightness variations in the light curve, radiations of X-ray, Ultraviolet, infrared, and cyclic variations in the orbital period of the binary.

Generations of Polidal and Toroidal magnetic Fields: It is a well known fact that the dynamo mechanism is likely cause of large scale magnetic field productions in the stars having convective layers (e.g., see parker, 1955). The differential rotation between the radiative core and convective envelope, winds up the field and causes a deformation (shearing) of the poloidal field which, in turn, generates an additional toroidal field component and thus creates a Lorentz force which counteracts the shear due to the poloidal field.

The effects of magnetic fields on the mass and angular momentum transfer and / or loss of both the companions are quiet appreciable. In a close binary, where the spin and orbital angular momenta are strongly coupled. This stellar spindown, forces a decrease in the orbital period of the system even without mass transfer.The coupling constant depends on the magnetic field strength and can be important if the field is strong enough (on the order or few mega gauss). Another effect of the magnetic field is to alter the spin through torquing of the star by mass outflow (see next section).

5. Magnetic braking

The net results of the mass exchange is a mass transfer from the primary to secondary during whole contact phase (Huang et al. 2007). In addition the magnetic braking is a common phenomenon to all the contact binary stars (see Bradstreet and Guinan 1994; Huang et al. 2007).

According to Bradstreet and Guinan (1994), Stepien (1995, 2006) the role of AM loss is crucial in the formation and evolution of the contact low mass binary stars. The magnetized star winds move outward from the active star, but are twisted due to rapid rotation of the star. Charged particles in the star wind get trapped in the magnetic field of the star and are dragged along the field lines. The result is Angular Momentum (AM) transfer from the star by magnetic field to the charged particles. As the winds leave the star surface they are dragged by the magnetic field which, in turn, slows down the rotation of star. For close binaries in which synchronization of rotational and orbital period is expected, loss of rotational angular momentum occurs at the expense of orbital AM. As a result, the period decreases (consistent with the observations) i.e., the components spin up and approach one another to form a single rapid rotating star (see Stepien 1995; Skumanich 1972). As stated by Stepien (1995, 2006) contact binary stars are magnetically very active and it is generally accepted that they lose mass and Angular Momentum (AM) via magnetized wind. Moreover the separation of the components is relatively low. Therefore, one expects the magnetic field interactions between the two components to be intensified and consequently its effect on the AM loss to be enhanced, due to the formation of magnetic loops between the surface magnetic fields of the components (see Fig 2 & 3). This statement is consistent with the Bradstreet and Guinan (1994) that the magnetic torque produced by magnetic field in the wind depends on the strength of

magnetic field. But the details of this idea and its quantitive formulations and experimental verifications will remain a challenge for the future.

The particles in the stellar winds that leave the star radially, at the stellar surface, their tangential velocity components are equal to the rotational surface velocity of the star. (e.g., for the Sun this velocity $v_{surf} = 2km/s$). When the same particle are traveled to outer space, it is expected to slow down to much lower velocities at large distances (e.g. for the Sun particles at earth distance, $a = 1.5 \times 10^8 km$, $v_{surf} = \frac{R_\odot}{a} \times 2 \simeq 1 \times 10^{-2}$ provided the angular momentum (of the star is conserved). But in the case the Sun, the particles velocities measurements by spacecrafts (e.g. Helios) is in order of 1-10 km/s. That is $10^2 - 10^3$ times faster than the expected velocities, the cause is that charged particles travel along the twisted open field lines and not just radially outwards. Therefore the magnetic energy of the field per unit volume must be much larger than the particle's kinetic energy and thus its trajectory is dominated by direction of magnetic field lines rather than gravitional field (see Strassmier 2001) and references there in). If some of the stellar magnetic field lines are open and reconnect, with companion star, then the particles either may collide with the parties which were guided by the companion star along the field lines in similar fashion to the primary star, or may fall in to the atmosphere of the companion star. (see the Figs. 2 & 3). These charged particles would carry the angular momentum of the star with themselves.

With this picture in mind, as explained earlier, the magnetic field lines are bent due to rapid rotation of the star, their curvature cause a counteract force on the surrounding stellar plasma if we assume that magnetic poles are coinciding with the rotation poles, then the dissipated angular momentum is very small and braking is almost negligible. But if field is anchored at or near the equatorial plane then the braking would be strongest and therefore maximum angular momentum is removed. Observations indicate that magnetic braking must be very effective for the observable surface, is larger in the late F-K type stars.

Due to tidal interaction between the components in binary systems, the component stars rotate much faster (10-100 times) as compared to a single star, therefore one expects the magnetic fields production in the surfaces (subsurface) of the components in binaries containing one or both components as late (F-K) type stars to be much stronger as compared with a single star (Yuan & Quian, 2007, eq. 7) the magnetic force is sensitive to (a^{-4}), the central separation between the components, but face to face separation between two components is much smaller as compared to central separation (i.e., a). The two magnetic fields as pictured above are superposed (see Fig. 4)

There are some observational evidences to support the above picture. Lestrade (1996) detected radio emissions from intra - binary region of the stars UX Ari and 2 CrB, which he attributed to gyro synchrotron process associated with large scale magnetic fields. Siarkowski (1996) used X - ray light curves of RS CVn binary AR Lacertae to map spatial structure of its corona, and found regions of enhanced X - ray emission and extended structures that interconnect the two stars. Gunn et. al. (1999) presented radio interferometeric observations of Algol- type binary V 505 Sagittarii and modulated radio flux density levels with evidence of eclipses of the emission regions of both conjunctions of the binary. The form of the light curve obtained implied that the radio source involves at least some enhanced emission in the intra - binary active regions. Gunn et. al. (1994), made EUV radio observations of active RS CVn binary CF Tucanae, their observations indicated an, active intra - binary region and field interaction in active close binary (see Figs. 2 & 3)

Uchida and Sakurai (1985) discussed the formation of corona and origin of flares in RS CVn binaries having starspots, and interpreted in terms of reconnection of the magnetic flux tubes
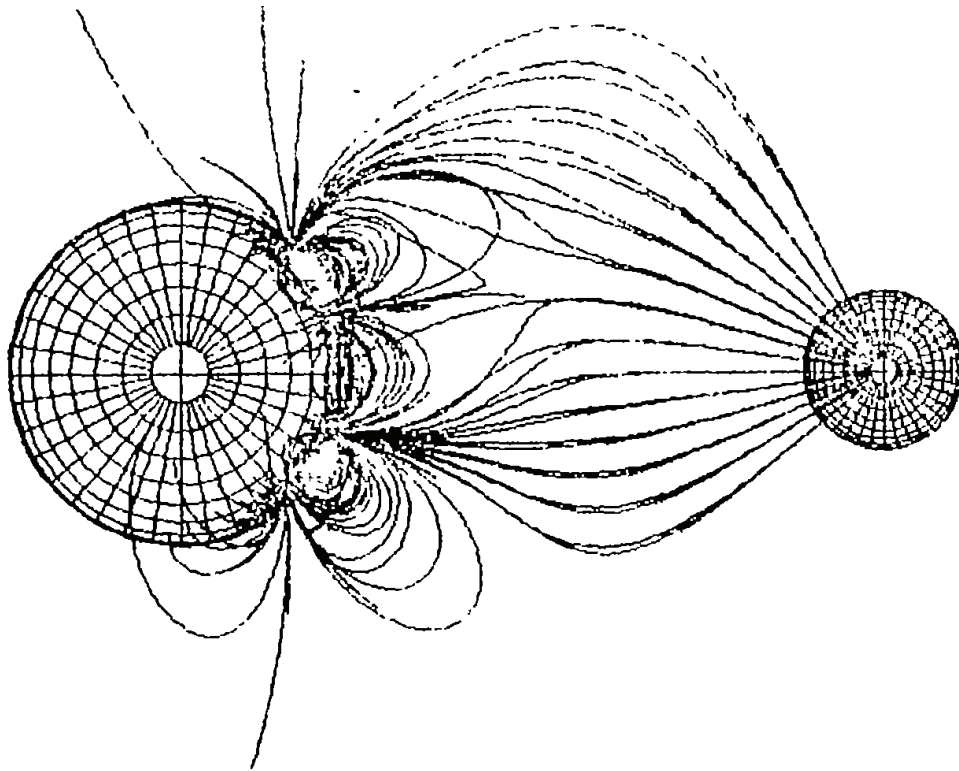
Fig. 2. Formation of large scale magnetic loops between two components of a binary star.
(Taken from Uchida & Skurai 1985)

of the companion star, they found that the injection of the hot plasma in to the large scale
Pole - to - spot connections was required to explain the extended corona with large emission
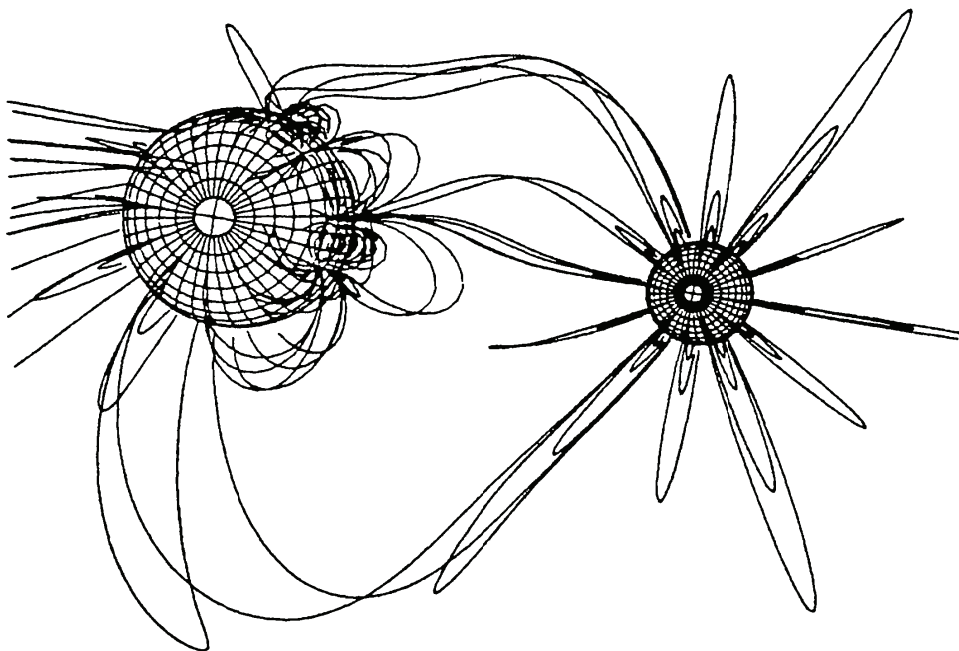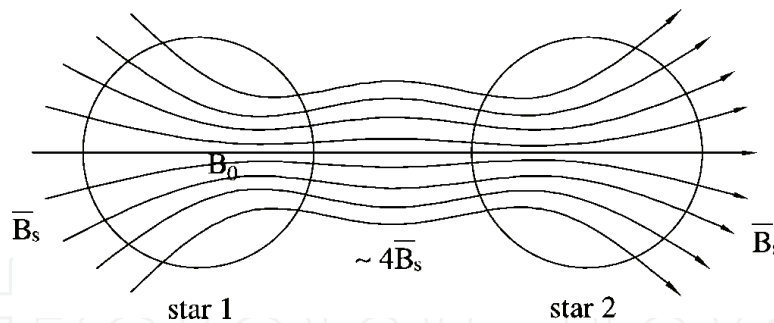measure they attributed this to the sweeping - pinch mechanism (see Uchida & Shibata, 1984)

Fig. 3. Formation of large scale magnetic loops between two components of a binary star.
(Taken from Uchida & Skurai 1985)

Fig. 4. Schematic sketch of magnetic field structure for a RS CVn binary star when both the components are magnetically active (Taken from Yuan & Quian 2007)

associated in the twisted magnetic flux tubes which emerge and reconnect with the flux tubes connecting poles and spots. Uchida & Shibata (1985) proposed a jet formation mechanism in which a packet of the toroidal component of magnetic field ($B\phi$) plays a role. Such a packet of toroidal field produced by the action of rapid rotation of the star in the region where $\beta = \frac{P_g}{P_m} \gg$ 1. They showed the jet can be accelerated when toroidal component of the field emerges from the $\beta >> 1$ region to the $\beta \ll 1$ region. When this happens a progressive pinch is produced through the relaxation of the field and mass is ejected out by pinch near the magnetic axis and also by $\mathbf{J} \times \mathbf{B}$ force in the twisted field region surrounding the axis.

6. Conclusions

In Algol type binaries one outcome of conservative mass transfer through Roche lobe filling mechanism of late secondary component is circumbinary disk, which can significantly influence the orbital evolution and cause the orbit to shrink on a sufficiently long time scale. Rapid mass transfer in Algols with low mass ratio can also be accounted for by this scenario. The observed decrease in orbital periods of some Algol binaries (see Manzoori, 2007, 2008 manzoori & Ghozaliasl 2007) suggests OAM loss and magnetic braking mechanism, during the binary evolution.

One of the interesting evolutionary consequences of mass transfer discovered in recent years, is the formation of double contact binaries. It seems the concept of double contact binaries first was introduced by Wilson (1979), as type of close binary which occurs only for nonsynchronism, the binaries in which both components fill their limiting lobes, naming them as double contact may be misguiding, because they do not even have a single contact point. This can occur, when at least one of the components rotates faster than synchronously, so that its limiting lobe is smaller than the respective Roche lobe (and the limiting lobe would be bigger than Roche lobe if it rotates slower than synchronously). The situation can occur as a natural consequence of mass transfer, because transfer normally spins -up an accreting star by converting orbital to rotational angular momentum.

As stated earlier in section 1, one of the main characteristics of (semidetached, Algol- type) binaries is mass transfer due to Roche lobe filling of late secondary component. Such mass - exchange will spin -up the mass accreting star (most of whose mass is transferred material, by the end of rapid phase of mass transfer). But according to Wilson et al. (1985) this rapid rotation will be damped quickly, as soon as mass transfer is stopped. Among semidetached systems there are few members which show asynchronous rotation, see table 1 of the Wilson and Twigg (1980). Thus, near to or after the end of rapid phase of mass transfer, the mass losing star would normally be found to fill its Roche lobe (rotating synchronously), while the

accreting star (or perhaps only its outer envelope) may have accommodated all of its capacity of the angular momentum which can hold, and so fill its limiting "rotational" lobe. According to Wilson and Caldwell (1978) the β- Lyrae and V356 Sgr and also U Cep and some of the Algol type systems are most likely candidates of double contact binaries. A main evolutionary consequence of their finding of double contact is that, since the accreting star after filling the limiting lobe will not be able to accommodate any more of the new high angular momentum material transferred by donor star, therefore such a system must find an alternate way for accommodation of the transferred matter, as first noted by Wilson and Caldwell (1978); this is a probable explanation for the thick circumstellar disks seen in β Lyr and V356 Sgr, and is perhaps related to numerous strange effects seen is U Cep (see Manzoori 2008). Notice that the existence of double contact systems introduce a symmetry in to the morphology of close binaries, in that stars may fill lobes exactly not only as a result off mass loss, but also as a result of mass gain.

The disk formed as mentioned, reduces a substantial fraction of the primary's light and therefore the star appears relatively under luminous, therefore it should make primary eclipse shallower than expected (see Manzoori 2006, 2008). For the same reason it would reduce also the irradiation of the secondary light by the primary, (reduces reflection effect), if the disk emits relatively little light of its own, the effect of its eclipse by the secondary star will be slight, but the eclipse of the secondary by the disk should be appreciable. Thus secondary eclipse should be wider than primary eclipse, and should also be deeper than it would be without an eclipse by the disk. One of the main conditions of the existence of double contact phase in the evolution of binary stars is nonsynchronous rotation of mass accreting component reaching the centrifugal limit. Naturally a star can not exceed its limiting rotational lobe because its equatorial matter would then be centrifugally unbound (see Wilson, 1983). The discovery of only very few members of this type of binaries, might be due to relatively brief time scale for binary to spend in double contact phase according Li et al. (2006).

According to Bradstreet and Guinan (1994) in close binary systems with period $P < 0.5d$, where tidal forces are strong enough to cause synchronization of the components, the role of spin -orbit coupling becomes important in evolution of the binary and angular mentum loss from the system through magnetic braking spin up with time, and orbital period decreases. Consequently magnetic activity of the stars increases. This process can cause a detached binary composed of late type components to become a short period contact W UMa - type binary. Webbink (1976, 1985) stated that in short period contact binaries with period $P < 0.5d$, after formation the loss of angular momentum through gravitational radiations play an important role in the evolution of the system and loss of angular momentum can ultimately lead to the coalescence of the binary system in to a single star. It is believed now the rapidly rotating F-K Com G - type gaint stars with intense H_α emissions are formed in this way. According to Stepien (1995; 2006) W UMa stars are magnetically very active and it is generally accepted that they lose mass and Angular Momentum (AM) via magnetized wind. Gazeas and Stepien (2008), analyzing over hundred cool contact binaries, found several correlations among the geometrical and physical parameters and they stated that "the coalescence of both components in to a single fast rotating star, is the final fate of contact binaries". This statement is not agreed with that of the Li et al. (2005). Li et al. in a series of three papers (2004a; 2004b; 2005) discussed the structure and evolution of low mass contact binaries, with and without spin and orbital angular momentum loss, and taking in to account effects of energy transfer, with negligible gravitational radiation. They presented an ultimate model of W UMa systems exhibiting cyclic evolution around a state of marginal contact, in time scales of about 6×10^6 yr,

without loss of contact, if spin angular momentum of both components are included; 9×10^6 yr, if spin angular momentum of both components are neglected. According to them, the ratio of spin angular moment of both components to the orbital angular momentum of the system becomes larger as the evolution proceeds, so that the system would then coalesce in to a rapidly rotating star, when the spin angular momenta of both components become more than one third of the orbital angular momentum of the system. Hence the cyclic evolution mentioned for the contact binary systems can not last forever. It only lasts about 7×10^9 yr, in good agreement with the observational result of old cluster NGC188; containing at least four W UMa type stars.

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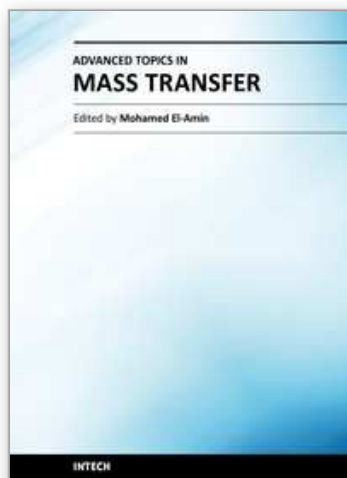
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Advanced Topics in Mass Transfer

Edited by Prof. Mohamed El-Amin

This book introduces a number of selected advanced topics in mass transfer phenomenon and covers its theoretical, numerical, modeling and experimental aspects. The 26 chapters of this book are divided into five parts. The first is devoted to the study of some problems of mass transfer in microchannels, turbulence, waves and plasma, while chapters regarding mass transfer with hydro-, magnetohydro- and electro- dynamics are collected in the second part. The third part deals with mass transfer in food, such as rice, cheese, fruits and vegetables, and the fourth focuses on mass transfer in some large-scale applications such as geomorphologic studies. The last part introduces several issues of combined heat and mass transfer phenomena. The book can be considered as a rich reference for researchers and engineers working in the field of mass transfer and its related topics.

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