Magnetic Stars, 2011, pp. 86 – 103

A Different Look at Cool Contact Binaries

Stępień K.

Warsaw University Observatory, Warsaw, Poland

Abstract. A brief history of the discovery of W UMa–type eclipsing variables, identified later as cool contact binaries is presented. Further, the main properties of these binaries are discussed and the thermal relaxation oscillation model (TRY) is presented. The model explains two main observational properties of W UMa–type stars: the geometry of the binary and the eclipsing light curves. However, the TRO model was developed under the assumptions, some of which turned out to be incorrect. In addition, some of its predictions are not in agreement with observations.

In reaction to these problems, a new evolutionary scenario, developed by the present author is presented. It assumes that W UMa–type stars are old objects which have passed the mass transfer episode with the mass ratio reversal. Their structure reminds the Algol–type stars, except that they have smaller angular momenta. The model is in good agreement with observations.

The evolutionary model is supplemented by the energy transfer mechanism. It is shown that the lack of hydrostatic equilibrium in a common envelope of the contact binary results in a large–scale flow of matter from the more massive primary to the secondary. The stream matter has a higher entropy than the surface layers of the secondary, hence it flows atop of them. The Coriolis force keeps the flow close to the equator. The stream encircles the secondary and returns to the primary. Because the heat capacity of the stream matter is much larger than the energy, radiated away during the journey around the secondary, the stream temperature hardly decreases. In a stationary situation the stream blocks the core energy of the secondary, flowing beneath, but due to an inconsiderable modification of the convective zone this energy is radiated away by the polar regions, not covered by the stream. The model predicts very similar temperatures of the primary and secondary, in agreement with observations.

Key words: stars: contact – stars: eclipsing – stars: binary – stars: rotation – stars: evolution

1 A Brief History of W UMa–type Binaries

When measuring the photometric magnitudes of stars for the *Potsdam Photometric Durchmusterung*, variability of the star BD +56 deg 1400 was detected. The star was subsequently observed several times and its light curve was determined (Müller & Kempf, 1903). It is interesting that their paper published in *The Astrophysical Journal* was translated from German and was published nearly simultaneously in reports of the Berlin Academy of Sciences. The authors correctly

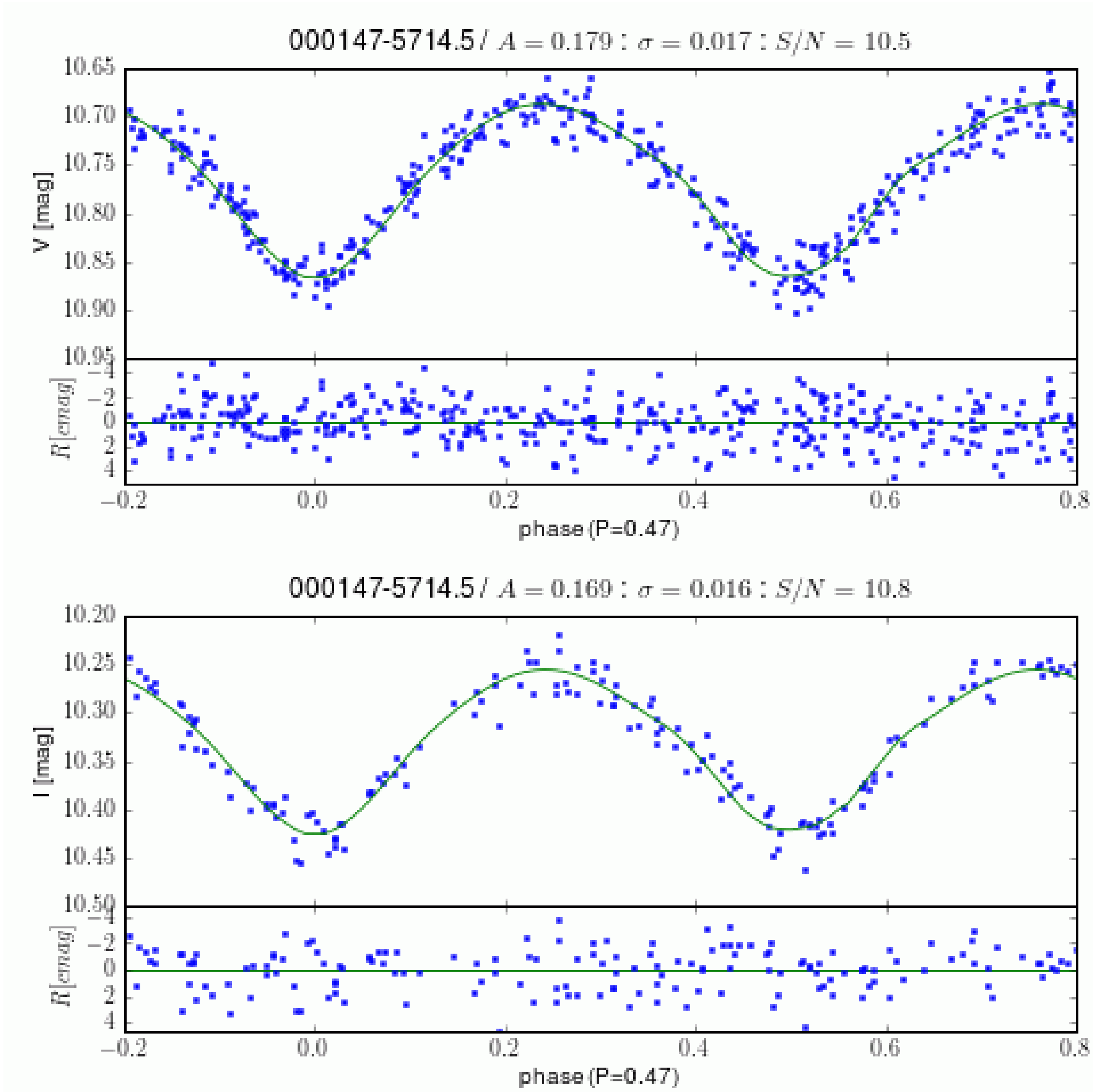

Figure 1: An example of the light curve of a W UMa–type star obtained recently within the ASAS photometric survey program (Pilecki, 2010)

identified the star as an eclipsing binary but they assumed that it was an Algol–type binary with only one minimum visible. The resulting period was about 4 hours — the shortest known to date. When discussing the possible reasons for variability, the authors also considered two nearly identical stars on a very tight orbit which eclipse each other, producing two nearly identical minima. However, they concluded that there would be a problem with stability of such a system.

Russell (1912) accepted the interpretation of the light curve as resulting from an Algol–type variability, rectified it and solved. He concluded that the primary was unusually dense, with an average density two times higher than that of a normal Main Sequence (MS) star of the same spectral type. Such a high density posed a problem for the stellar evolution. The problem was solved when it turned out that the star has in fact a period of 8 hours and two nearly identical minima (Russell et al., 1917). The star received a designation "W UMa" and became a prototype of a new class of variables. Since then many thousand eclipsing binaries similar to W UMa have been detected. An example of the recently obtained light curve of a W UMa–type binary is shown in Fig. 1.

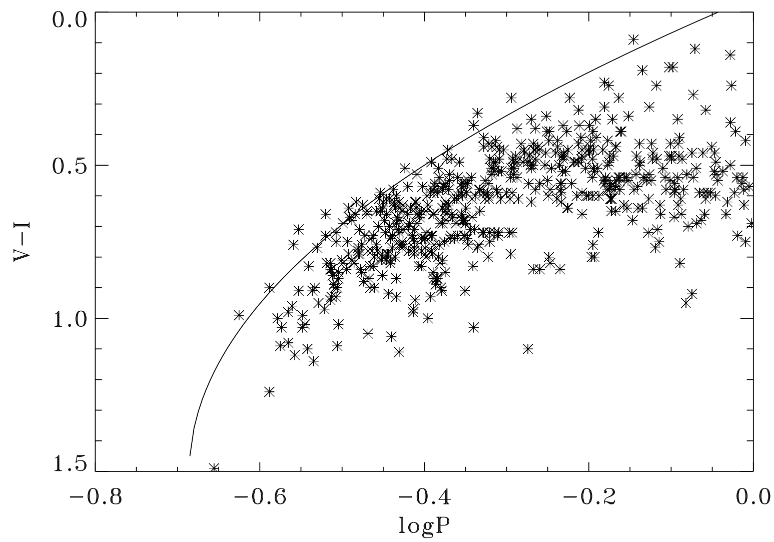

Figure 2: A recent version of the period − color diagram, based on observations from ASAS, reduced by Pilecki (2010)

The simultaneous solution of light and radial velocity curves showed that a W UMa–type binary consists of two cool stars surrounded by a common envelope lying between the inner and outer Lagrangian zero velocity equipotential surfaces (Mochnacki, 1981) and possessing nearly identical mean surface brightness. The more massive, primary component is a MS star. It seemed reasonable to assume that the secondary was also a MS star particularly because it was believed for a long time that contact binaries can be formed in the process of a protostar fission. Subsequent numerical simulations favoured, however, an early fragmentation of a protostellar cloud (Boss, 1993; Bonnell, 2001) rather than fission. Such stars should have an orbital period of at least 2 − 3 days at the birth line of T Tauri stars because their sizes are a few times larger than the solar radius at that time (Stahler, 1988). Later, a binary may lose a part of the initial angular momentum (AM) due to a very high level of activity of T Tauri stars resulting in an intense stellar wind. The AM loss (AML) of a close binary with components rotating synchronously with the orbital period results in tightening of the orbit. Since, however, the time scale for AML due to magnetised wind is longer than the lifetime in the T Tauri phase, the expected period shortening is rather limited. The observations support this conclusion. We do not observe binaries with orbital periods shorter than one day in young stellar clusters (Kaluzny & Rucinski, 1993) or among T Tauri–type stars (Mathieu, 1994).

Kuiper (1941) noted that contact binaries with unequal zero–age components cannot exist in equilibrium because the radii of the components must fulfil two mutually contradictory conditions: one resulting from the mass–radius relation for zero–age stars, and the other relating sizes of the Roche lobes, identical in this case with the stellar sizes, to stellar masses. He noted that such a system is out of hydrostatic equilibrium, which forces the large–scale circulations, carrying mass between the components. The flow stops only when the masses of both components are equal. The fact that contact binaries with unequal masses are nevertheless observed is known as the "Kuiper paradox". Eggen (1961) discovered the relation between the colour of a W UMa–type binary and its period, known as the period–colour relation. Its recent version, based on the observations obtained by the ASAS team and reduced by Pilecki (2010) is shown in Fig. 2. An upper bound corresponds roughly to the bluest stars for their period, hence least evolutionary advanced. Unless the mass ratio is close to unity, the colour index of a binary is determined by the primary. When it evolves, its colour index becomes redder and its size increases, and hence the orbital period must also increase

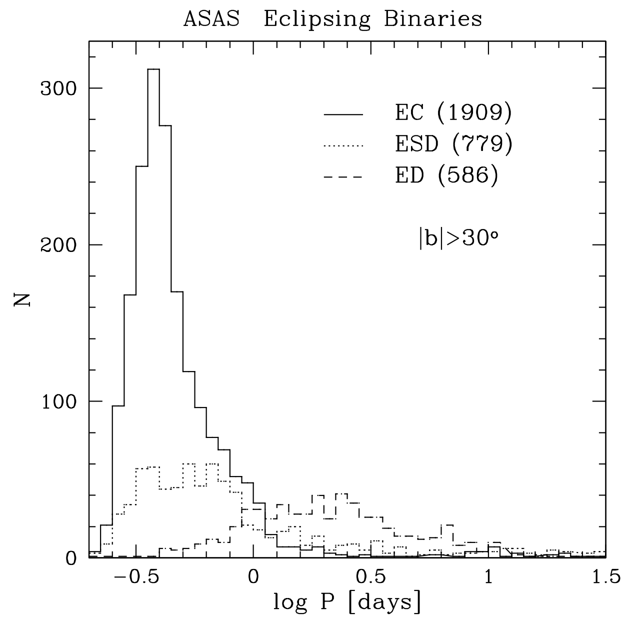

Figure 3: Period distribution of W UMa–type stars from the ASAS photometric data (solid line) compared with period distribution of semi–detached (dotted line) and detached (broken line) eclipsing binaries. The figure is taken from Paczyński et al. (2006).

to accommodate a larger star. So, the direction of evolution of a binary in Fig. 2 is towards the longer periods and redder colour (Rucinski, 1998).

An important contribution to the close binary research was done by Kopal (1955) who introduced the classification of close binaries based on the relation of component sizes to the respective Roche lobes. Binaries with the components well inside their Roche lobes are called detached, those with one component filling its Roche lobe are called semi–detached and the ones with both components filling their Roche lobes are called contact binaries. This nomenclature has been used since then.

2 Main Properties of Cool Contact Binaries

W UMa–type binaries are examples of cool contact binaries with a favourable inclination of the orbit to the line of sight so the eclipses are observed. We define cool contact binaries as binaries with orbital periods between 0.2 and 1 day, and initial component masses on the zero age main sequence (ZAMS) less than $1.3\,M_{\odot}$, filling their critical Roche lobes and having a nearly identical surface brightness. The lower limit for the orbital period is empirically found — no W UMa–type binaries with periods significantly shorter than 0.2 d are known. The upper limit is somewhat arbitrary — there is no sharp upper limit on the orbital period of these stars. The upper limit for the initial mass is set at the value where the subphotospheric convection first appears. Its value is approximate. The requirement of equal surface brightness assures that the binary possesses a common envelope in which the energy transfer between the components takes place.

The period distribution of about 2000 cool contact binaries, observed within the ASAS project, is taken from Paczyński et al. (2006) and shown in Fig. 3. It is seen that the distribution is apparently peaked at the period 0.38 d. After correcting the distribution for a deficit of weak, short–period variables the maximum shifts to 0.27 d (Rucinski, 2007). Thus the corrected distribution is strongly asymmetric with a sharp decrease towards short period limit.

The sample of well–observed W UMa–type stars with accurate spectroscopic mass ratio and good photometric curve is much less numerous than the ASAS data (Gazeas & Stępień, 2008).

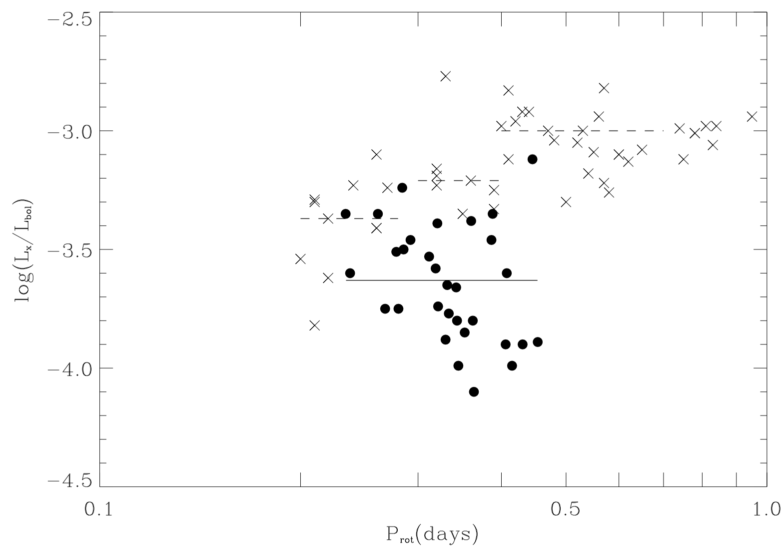

Figure 4: The X–ray flux of several W UMa–type stars (filled circles) compared to the fluxes of single active stars (crosses). The figure is taken from Stępień et al. (2001).

When the radii of the components of binaries with well determined parameters are plotted against their masses, we can see that more massive components (primaries) are indeed MS objects, whereas less massive components (secondaries) are oversized for their masses and lie in the region, occupied by stars with low mass helium cores. This is very reminiscent of the mass-radius diagram for the components of Algol–type binaries (see Fig. 3 in Ibanoğlu et al., 2006). It seems justified to assume that secondaries of W UMa–type stars are also evolutionary advanced, just as it is in the case of Algols.

No direct measurements of the magnetic field on W UMa–type stars exist, but there are very convincing arguments that they possess strong surface fields. As the observations show, all cool, rapidly rotating stars show very high level of chromospheric–coronal activity. Surface magnetic fields have been detected on many single active stars. The field intensity is well correlated with other activity indices, like X–ray flux or emission flux observed in the cores of chromospheric lines (Stępień, 1994). The observations are supported by theoretical considerations of the dynamo mechanism. The mechanism is operating in rotating stars with subphotospheric convective zones and its efficiency increases with increasing stellar rotation velocity. Components of W UMa–type stars are rapidly rotating and possess convection zones. The observations of these stars show that they belong to the most active stars. Their chromospheric emission fluxes are among the highest observed (Vilhu & Walter, 1987). The X–ray fluxes are somewhat weaker than the fluxes of single stars with the same rotation periods (Fig. 4), but they are, nevertheless, at the level of $10^{-3} - 10^{-4}$ of the bolometric flux.

Light curves of many W UMa–type stars vary strongly from one season to another. Perhaps the most spectacular case of such variations is shown by one of the stars observed within the project OGLE (Rucinski & Paczyński, 2002). Pilecki (2010) also observed numerous examples of such variability. One of them is shown in Fig. 5 which is copied from his PhD Thesis. The most probable explanation of such a variability assumes the existence of dark starspots which cover a substantial part of one or both components and the coverage changes in time. As a matter of fact, the satisfactory solution of a single light curve often requires adding one or more spots. Finally, the explanation of the so–called “W phenomenon”, which consists in a lower mean surface brightness of the primary than the secondary, also involving a high coverage of the primary by cool spots.

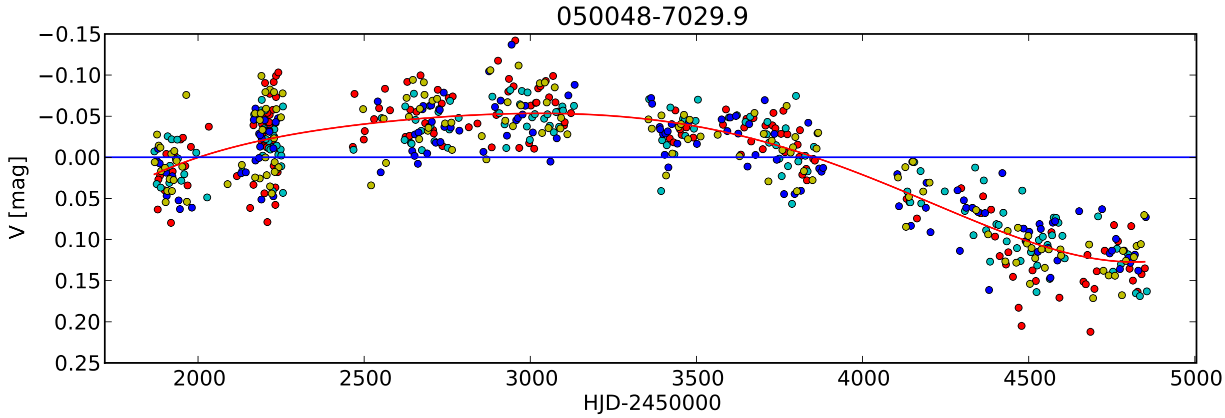

Figure 5: Seasonal variations of the average magnitude of one of the W UMa stars discussed by Pilecki (2010)

The presence of all these phenomena points towards the existence of strong surface magnetic fields. Based on this we can include cool contact binaries into the category of stars, possessing magnetic fields.

Except for very cool giants, magnetic activity results in formation of a hot corona surrounding the star. The corona emits X–rays, but it also evaporates into space in the form of an ionized wind, which sweeps away the frozen–in magnetic field. Assuming an approximate conservation of the specific AM, the wind rotation slows down when the wind matter moves further from the star. As a result, the curved magnetic field lines exert a torque on the star carrying away its AM and braking its rotation. Observations of young single cool stars show that they rotate rapidly with periods of the order of 1 day, but the rotation rate decreases with stellar age up to the periods on the order of several tens of days. We assume that W UMa–type stars possess similar winds. In this case the result of AML is different. The components of cool contact binaries rotate synchronously with the orbital period. The rotation of each component cannot slow down because the tidal forces maintain the synchronisation. Because of that the AML by the winds results in a decrease of orbital AM, orbit tightening and period shortening. In other words, the AML caused by magnetised winds results in the spin–up of both components. It is believed that close detached binaries with initial periods of a couple of days are the progenitors of cool contact binaries after they have lost a substantial fraction of the orbital AM via the magnetised winds of both components.

3 Thermal Relaxation Oscillation Model and the Old Paradigm

Lucy (1968) noted that the Kuiper paradox can be solved by assuming that both zero–age components have a common convective envelope with the same adiabatic constant and the CNO nuclear reaction prevails in the primary, whereas the p-p reaction prevails in the secondary. However, detailed calculations showed that realistic models can exist only within a narrow range of component masses, contrary to what was observed. Later Lucy (1976) considered a binary configuration with the components out of thermal equilibrium. A similar model was developed by Flannery (1976), Webbink (1976) and others. The model is known as the Thermal Relaxation Oscillation (TRO) model. The model assumes that the binary is in a global thermal equilibrium but each component separately is out of it. The energy is transported from the primary to the secondary via turbulent convection, forcing equal entropies in both convective envelopes, hence equal surface brightnesses. The sizes of both components oscillate around the corresponding Roche lobes with a cycle length equal to the thermal time scale and the binary alternates between two states: semi–detached and contact. The model has been later modified when it became apparent that we do not observe cool contact binaries on the ZAMS. In the modern version it consists of the following basic points:

- both components are MS stars, with primary possibly evolved from the ZAMS
- when a primary reaches its critical Roche lobe, mass transfer starts
- after receiving about $0.1\,M_{\odot}$ the secondary expands and a common envelope is formed
- the further mass transfer is blocked by the swollen secondary
- the convective energy transfer from the primary to the secondary results in equal entropies of both convective envelopes, hence the same surface brightness
- each component separately is out of thermal equilibrium but the binary is in global equilibrium. TRO forces the binary to alternate between the contact and semi–detached configuration
- luminosity increase of the primary due to its faster evolution drives the secular mass transfer from the secondary to the primary
- when the mass ratio reaches about 0.1, the secondary is tidally disrupted and a rapidly rotating single star is formed (FK Com? Blue straggler?)

The TRO model explains in a very elegant way two basic observational facts about W UMa–type stars: the Kuiper paradox, i. e. the geometry of the binary in which the primary is an ordinary MS star, whereas the secondary is also a MS star but swollen to the size of its Roche lobe by the energy transfer, and equal apparent effective temperatures of both components resulting in a characteristic light curve with two equal minima. It encounters, however, several difficulties. In particular, some of its basic assumptions seem to be incorrect and some of its predictions are at odds with the observations. Here we list the most important reservations.

The TRO model predicts that a binary alternates between two states: contact — when both stars fill their respective Roche lobes and there is a net mass flow from the secondary to the primary, and semidetached — when the primary still fills its Roche lobe but the secondary is within its Roche lobe and the mass flows from the primary to the secondary (Lucy, 1976). The time scales of both states should be comparable to one another. This prediction is not in agreement with observations showing that binaries within the same parameter range as the genuine contact binaries but with distinctly different depths of minima are quite rare (Rucinski, 1998). Additional effects, like stellar evolution and/or angular momentum loss (AML) can reduce the relative duration of the semidetached state (Robertson & Eggleton, 1977; Rahunen, 1983; Yakut & Eggleton (2005); Li et al., 2005). For high enough AML rate a binary can remain in the contact state all the time but then its lifetime as a contact binary must be as short as $\sim 10^8$ (Webbink, 2003). With such a short lifetime contact binaries would have to be rare in space, contrary to observations.

A recent photometric sky survey ASAS resulted in the detection of several thousand eclipsing binaries with periods shorter than 1 day. Their analysis showed a significant proportion of semi–detached systems. This would seemingly solve the problem and support the TRO model. However, a closer look at the sample shows that among the stars with periods shorter than 0.45 day there are virtually no semi–detached binaries (Pilecki, 2010) whereas a great majority of all known contact stars have periods within this range (Rucinski, 2007). The semi–detached binaries become very common among the systems with periods longer than 0.7 day where we observe very few contact binaries. So, the problem of the shortage of semi–detached systems among short period binaries still remains.

The TRO model was developed for the zero–age or slightly evolved stars. However, both theory and observations show that contact binaries are absent on the ZAMS and in young stellar clusters but they are very numerous in old open clusters with ages exceeding 4 – 4.5 Gyr and in globular clusters (Kaluzny & Rucinski, 1993; Rucinski, 1998, 2000). Large numbers of W UMa–type stars have been observed in the galactic bulge (Szymański et al., 2001). The analysis of kinematics of these stars in the solar vicinity showed that they are several Gyr old (Guinan & Bradstreet, 1988; Bilir et al., 2005). The time interval of 5 to 13 Gyr is long enough for a primary with mass between 1.3 and 0.9 $M_\odot$ to complete its main sequence (MS) evolution. We should thus ubiquitously observe W UMa–type stars with components possessing hydrogen–depleted cores. Such a star expands rapidly when moving towards the red giant branch and its evolution must very strongly influence the fate of the whole binary.

Recent accurate observations of close semi–detached binaries revealed numerous Algol–type systems with periods shorter than 1 day with the record–shortest period equal to 0.38 d (Rucinski & Lu, 2000). How were they formed? Classical Algols are formed by the mass transfer from the evolved primary with a hydrogen-depleted core to the secondary, which results in the reversal of mass ratio. Why some of close binaries reverse mass ratio but others, indistinguishable from them do not? Or perhaps they all do? It seems that we are still very far from understanding the process of mass transfer between the components of a close binary.

The last objection concerns energy transfer in a contact phase. If, instead of a turbulent convective transfer, large–scale circulations transport energy between the components, specific entropies of both convection zones do not have to be equalised. In fact, they may correspond to the weakly perturbed convection zones of single stars with the same masses and internal structure as the components of the binary.

Based on these facts a new model of a cool contact binary has been developed by the present author (Stępień, 2004, 2006a, 2006b, 2009).

4 New Evolutionary Scheme

The new model assumes that contact binaries originate from young cool close binaries with initial orbital periods of a few days. Both components possess subphotospheric convective zones necessary for generating surface magnetic fields. Cool stars with subphotospheric convective zones show magnetic activity with intensity increasing with the increase of rotational angular velocity. Assuming the synchronisation of rotation with orbital period we expect the activity level of each component to be at the very high, so–called “saturation” level. Magnetic activity drives stellar winds carrying away the spin AM which results in a decrease of the orbital AM. The orbit tightens and the components approach each other until the primary fills the critical Roche surface. This is followed by the Roche lobe overflow (RLOF). For an initial mass of the primary amounting to 1.3 $M_\odot$ and the period of 2 d the time scale for AML is close to the lifetime of the primary on the MS so the RLOF occurs when it is close or beyond the terminal age main sequence (TAMS) and its radius increases rapidly. The expanding star transfers mass to the secondary. The model assumes that the mass transfer proceeds in the same way as in Algols, i. e. after a possible phase of the rapid mass exchange resulting in a loss of thermal equilibrium of both components and a transient formation of the thick common envelope, both stars reach thermal equilibrium within a configuration with the mass ratio reversed. The present primary (former secondary) lands close to the ZAMS in the H–R diagram because it has been fed with hydrogen–rich matter, whereas the present secondary (former primary) is evolutionary oversized as its core is hydrogen depleted. The secondary continues its path to the red giant region building its helium core, and transfers matter to the primary. Mass transfer rate depends on two effects acting on the orbit in opposite directions: mass transfer results in its expansion, whereas AML tightens it. Interplay between these two processes determines the rate of evolution of a contact binary towards the extreme mass–ratio configuration which should ultimately end up in merging of both components. In some binaries the evolutionary effects of the primary may become important. In particular, when the primary reaches the TAMS it expands rapidly and the merging process should dramatically accelerate.

Phase I of the presented evolutionary scenario describes an approach to contact. We apply the Roche model for the description of the orbital parameters of the binary. The first model equation is the third Kepler law

$$P = 0.1159 a^{3/2} M^{1/2}\,, \tag{1}$$

where $M = M_1 + M_2$ is the total mass, a is the semiaxis and P is the orbital period. Here the masses are expressed in solar mass, the semiaxes in solar radius and periods in days. We also need the expression for the orbital angular momentum

$$H_{\rm orb} = 1.24 \times 10^{52} M^{5/3} P^{1/3} q (1+q)^{-2}\,, \tag{2}$$

with $H_{\rm orb}$ in cgs units, and finally the expressions for the critical Roche lobe sizes, approximated by Eggleton (1983)

$$\frac{r_1}{a} = \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})}\,, \tag{3}$$

$$\frac{r_2}{a} = \frac{0.49 q^{-2/3}}{0.6 q^{-2/3} + \ln(1 + q^{-1/3})} \tag{4}$$

where $q = M_1/M_2$ is the mass ratio. The empirical AML rate was originally derived by Stępień (1995) and recently updated for single cool stars of different mass (Stępień, 2006b). It is parameter–free and depends only on stellar parameters. We neglect any possible interaction between the winds of the binary components and assume that each component of a binary loses AM just like a single star. For very short periods of the order of a few days or less the formula reads (Stępień, 2006b; Gazeas & Stępień, 2008)

$$\frac{\mathrm{d}H_{\rm orb}}{\mathrm{d}t} = -4.9 \times 10^{41} (R_1^2 M_1 + R_2^2 M_2)/P\,. \tag{5}$$

Assuming that the saturation process also influences the AML, for the binaries with rotation periods shorter than 0.4 days the period P in Eq. (5) was replaced by 0.4. This is the approximate value of the rotation period for which the saturation of the X–ray flux starts (Stępień et al., 2001). No effect of supersaturation, occurring for still shorter periods and resulting in a decrease of activity was taken into account.

The magnetised wind carries away not only the AM but also mass. Wood et al. (2002) determined the mass loss rates of several single active stars and they derived an empirical formula, which can be extrapolated to the rapidly rotating stars being at the saturation level. In the limit, the formula reads

$$\dot{M}_{1,2} = -10^{-11} R_{1,2}^2\,, \tag{6}$$

where the mass loss rates are in $M_\odot$/year and radii — in solar units. Note that the above formula does not contain any free parameters neither.

The equations were integrated in time taking into account the evolutionary changes of the primary in a simplified way. The model was evolved until the size of the primary became identical with the size of the Roche lobe. At this moment phase II begins, which corresponds to the mass transfer from the primary to the secondary. To avoid additional free parameters, conservative transfer was

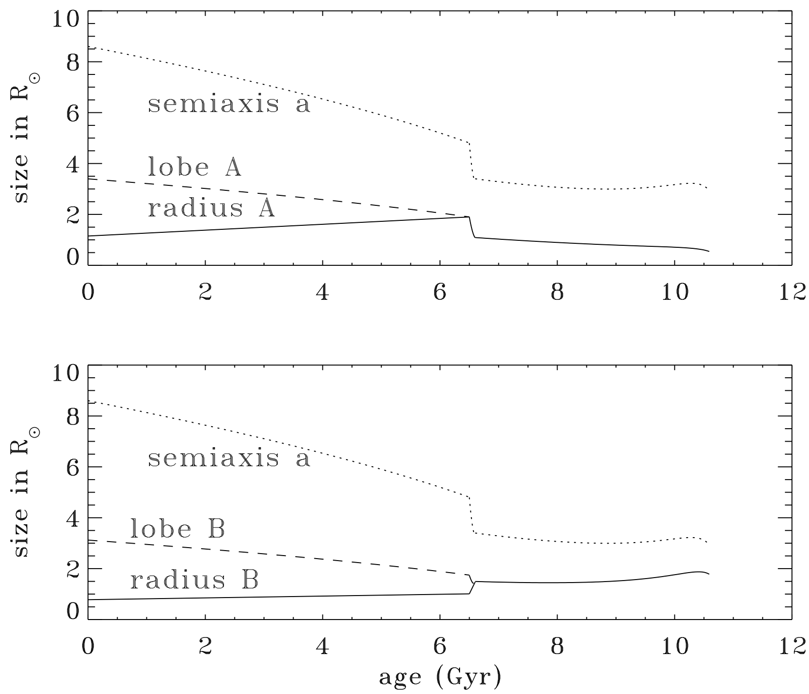

Figure 6: Time variation of semiaxis, stellar radii and the Roche lobe sizes of a binary with the initial masses of $1.2 + 0.6\,M_\odot$ and the initial orbital period of 2 d

assumed. It takes place on a dynamic or thermal time scale — both are much shorter than either evolutionary or AML time scales. Phase II ends when both stars reach thermal equilibrium after the mass ratio reversal and phase III begins. The present secondary fills its Roche lobe whereas the primary may or may not fill its Roche lobe. It depends on the amount of AM left in the system after the first two phases. If the secondary fills its Roche lobe we have a contact system, and if it is inside the Roche lobe, the system is of Algol–type. It is assumed in phase III that both components lose AM in the same way as single stars with the same masses and radii (rotation periods result from the assumption of synchronisation). In addition, a slow mass transfer from the secondary to the primary takes place. It results from the evolutionary expansion of the secondary which has a hydrogen–depleted core. Depending on the initial configuration, the secondary may still be in the MS phase or it may already possess a small helium core which is increasing as time goes on. The mass transfer rate between the components should result from the evolutionary calculations. However, taking into account uncertainties in the detailed modelling of advanced stages of evolution, the mass transfer rate was treated as a free parameter. As the results show, mass transfer rate in contact binaries can change in a very narrow interval. A too high rate results in widening of the binary which becomes semi-detached. A too low rate results in a rapid tightening of the orbit followed by the overflow of the outer critical surface (Gazeas & Stępień, 2008). A fine tuning of the mass transfer rate permits a binary to exist in a contact configuration for a sufficiently long time.

Figure 6 presents the time variation of the semiaxis, stellar radii and Roche lobe sizes for a binary with the initial masses of $1.2 + 0.6\,M_\odot$ and the initial orbital period of 2 d (Stępień, 2006a). Phase I ends at the age of about 6 Gyr when the lobe A descends onto the surface of the star A (initially a more massive component). Phase II is very short (note a dip in the curve describing the size of the semiaxis, which corresponds to a short phase of the thick common envelope) and results in a contact configuration with the mass ratio reversal. Phase III ends when the mass ratio decreases beyond 0.1. Such a binary will very likely merge forming a single, rapidly rotating star (Rasio, 1995)

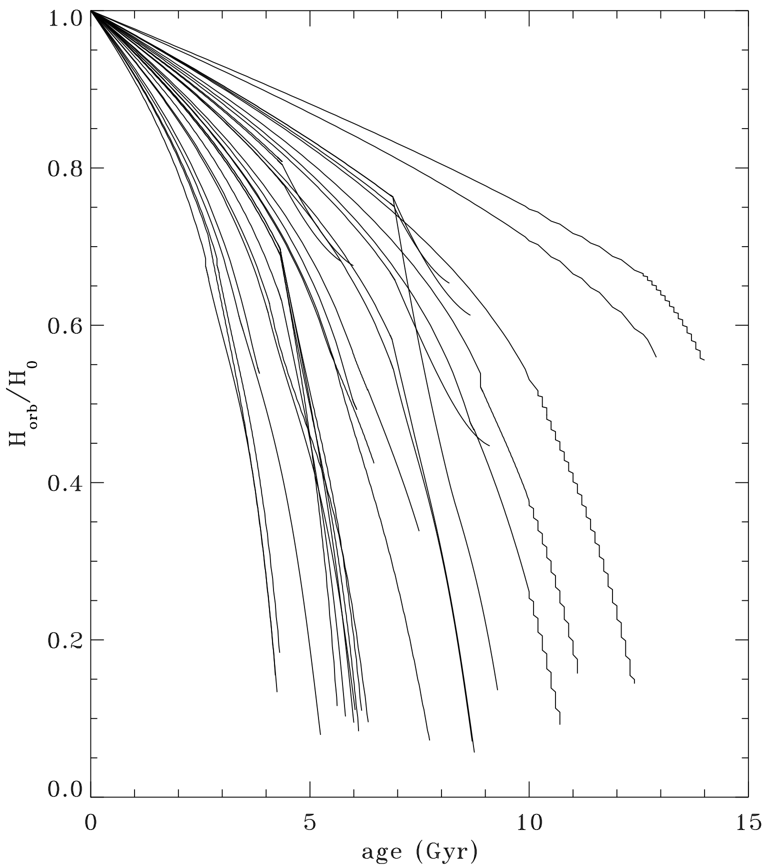

Figure 7: The time variation of the orbital AM ratio to its initial value for the considered binaries.

Several examples of binaries exist with the parameters corresponding to different phases. The binary XY UMa has the following parameters: $P = 0.48$ d, masses $1.1 + 0.66\,M_\odot$, radii $1.16 + 0.63\,R_\odot$, the filling degree of the Roche lobes of 68% and 22%, respectively (Pribulla et al., 2001). The binary is close to the end of phase I. In less than 1 Gyr the primary will reach the RLOF and the mass transfer will start. The star V361 Lyr seems to be in phase II. It has the following parameters: $P = 0.31$ d, masses $1.26 + 0.87\,M_\odot$ and radii $1.02 + 0.72\,R_\odot$ (Hilditch et al., 1997). The primary fills its Roche lobe and the stream of matter is visible, hitting the surface of the secondary and producing a hot spot clearly visible in the light curve of the eclipsing variable. The secondary fills 90% of its Roche lobe. Note that in spite of the strong mass flux received by the secondary, the star is not inflated, contrary to the predictions by theoretical models of mass transfer (Webbink, 1976; Sarna & Fedorova, 1989; Yakut & Eggleton, 2005). It means that either V361 Lyr is observed in a very short initial phase mass transfer and the secondary will soon inflate, or mass transfer from the more massive to the less massive component of a close binary does not necessarily lead to an immediate inflation of the latter star. Several eclipsing binaries can be identified as evolving in phase III: W Crv was already mentioned as the shortest–period Algol which very soon should transform into the contact configuration, whereas AW UMa and SX Crv, with mass ratio beyond 0.1 approach merging of the components, which is the end of phase III.

I have recently calculated a set of 27 evolutionary models of close binaries with three different initial periods: 1.5, 2.0 and 2.5 d. For each initial period the evolution of 9 binaries was followed. Their initial masses are: 1.3 + 1.1, 1.3 + 0.9, 1.3 + 07, 1.1 + 0.9, 1.1 + 0.7, 1.1 + 0.5, 0.9 + 0.7, $0.9 + 0.5$ and $0.9 + 0.3\,M_\odot$. The preliminary results are presented in a few following figures. Figure 7

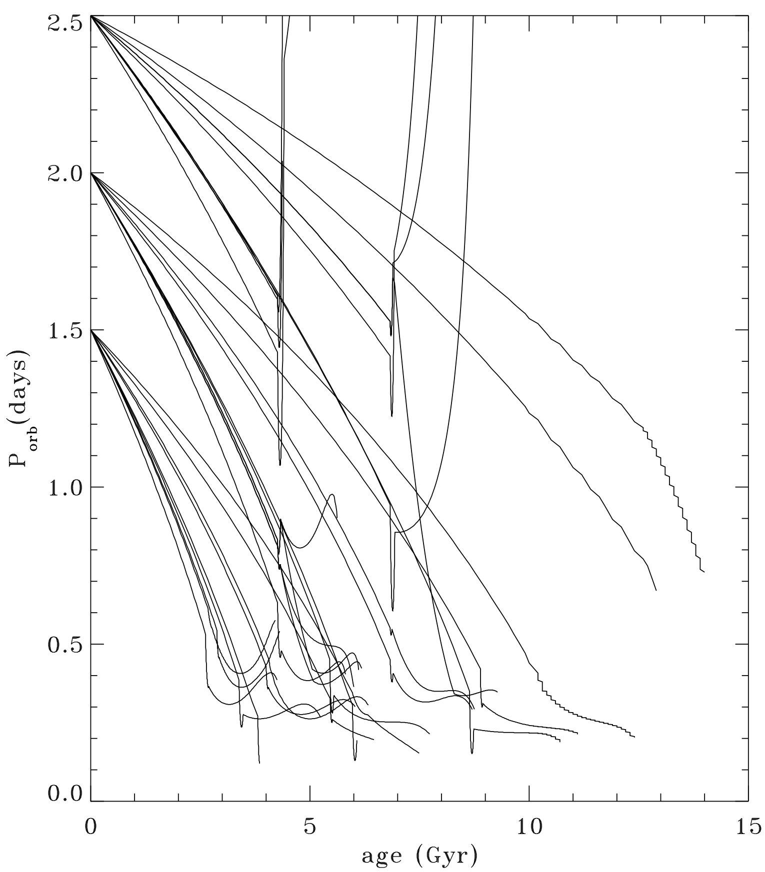

Figure 8: The time evolution of the orbital periods of the considered binaries. Depending on the mass transfer rate from the secondary to the primary some binaries became Algols with periods of several days.

shows a decrease of orbital AM in time, relative to its initial value. We can is see that the AML caused by the wind is very substantial. A majority of binaries lose 80 − 90% of their initial AM. The AML is the main driving force of evolution of the binary. Figure 8 shows how the periods of individual binaries change during the evolution. The mass transfer rates in phase III were adjusted to have contact configurations. In a few cases the curves bifurcate — two branches correspond to two different mass transfer rates. The lower rate results in a contact configuration, whereas an Algol–type binary is produced with a higher rate. The periods of Algols may reach several days. Figures 9 and 10 compare models with observations. The data from Gazeas & Stępień (2007) were plotted in both figures. Figure 9 shows the evolutionary tracks of modelled binaries in the period−AM diagram. The dotted lines correspond to the detached and semi–detached configuration, while the solid lines describe the evolution in a contact phase. The observed values are plotted as asterisks. Almost all observations are reproduced by the models. Some of the observations fall into the region of long periods and/or high values of AM, where the modelled binaries are not in contact. The inspection of the observational data of these binaries shows that the radii of the primaries are significantly larger than their ZAMS values, and their masses are larger than about 1.5 $M_{\odot}$. The present calculations assume that all the primaries in phase III lie close to the ZAMS because they are fed with hydrogen rich matter. Obviously, this assumption does not apply to the most massive primaries which evolve quite fast across MS and they burn hydrogen at a higher rate than they receive it from the secondary. As a result, their mean molecular weight increases, which corresponds

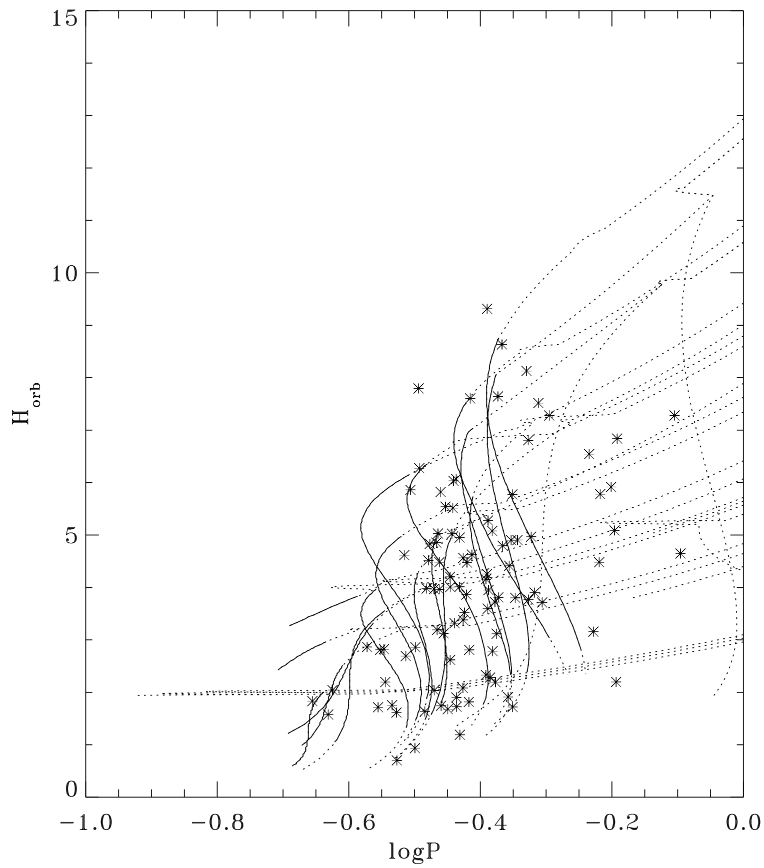

Figure 9: Period–AM diagram for the observed binaries (asterisks). The data are adopted from Gazeas & Stępień (2008). The evolutionary tracks of the modelled binaries are overplotted. The dotted parts correspond to the detached and semi–detached phase, whereas the solid parts of the tracks correspond to the contact phase.

to the evolutionary advancement. This conclusion is confirmed by Fig. 2, where several contact binaries with periods close to 1 day lie in the region, corresponding to the advanced evolutionary system. A new series of models needs to be calculated with evolutionary effects of the primaries taken into account. A few evolutionary tracks are plotted down to periods close to 0.1 d. Such short periods are non-physical, since in order to reach them, the age longer than the age of the Universe is needed. They are plotted just to show that even the oldest stars with low masses remain detached.

Figure 10 shows that the calculated tracks cover well the observed masses and mass ratios of the observed W UMa–type stars, which confirms the evolutionary scenario presented here. Again, some of the tracks are extrapolated beyond the observed values just to demonstrate the direction of evolution.

To summarize, the new evolutionary model of cool contact binary assumes that the binary is past the mass exchange with mass ratio reversal and the secondary is more advanced evolutionary than the primary. This solves the Kuiper paradox. Detailed calculations show that the secondaries in some binaries may have already built a small helium core, but in others their cores are only hydrogen–depleted to a degree depending on the initial orbital period and the initial mass of the original primary, which becomes a secondary after the mass exchange.

So far, nothing has been mentioned about the energy transfer between the components. As we remember, the TRO model explained not only the Kuiper paradox, but simultaneously provided an

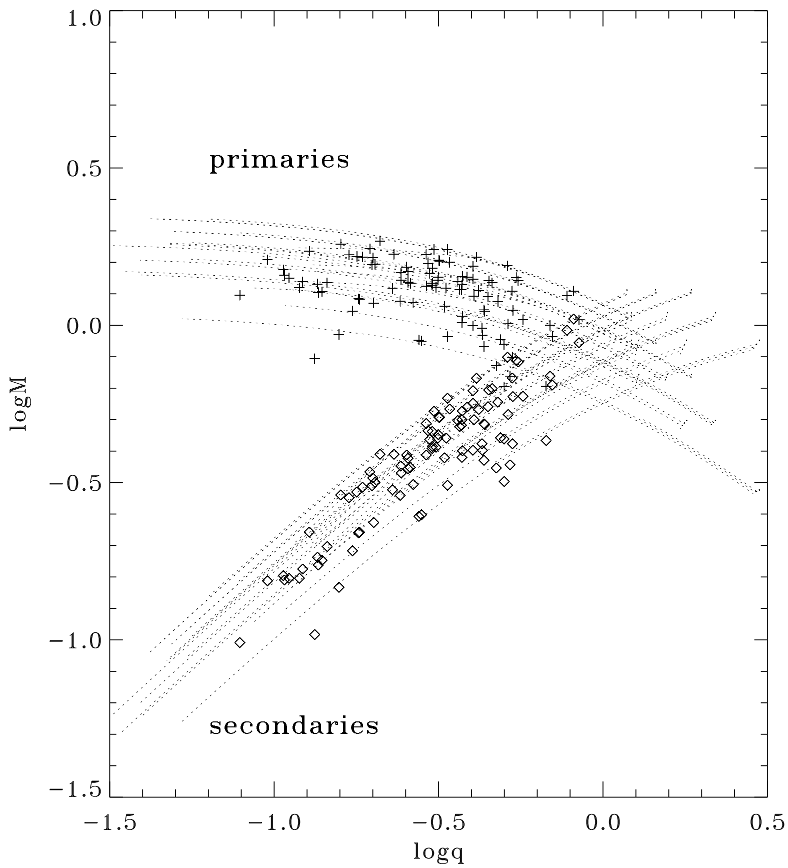

Figure 10: The observed component masses are plotted *versus* the mass ratio as crosses (primaries) and diamonds (secondaries). The evolutionary tracks of the modelled binaries are overplotted, starting at the right hand ends from their initial values.

explanation of the observed light curves with both eclipses of the same depth. The present model does not explain the latter effect. It has to be supplemented with the mechanism of energy transfer. The next section presents such a mechanism and compares it with observations.

5 Energy Transfer Between the Components of a Cool Contact Binary

A contact binary consists of two cool stars surrounded by a common envelope lying between the inner and outer critical surfaces (Mochnacki, 1981). Because the stars have different luminosities at the inner critical surface, the common envelope cannot be in hydrostatic equilibrium. Even if we assume constant pressure on a given equipotential surface, a difference occurs on the other surfaces within the common envelope due to different pressure scale heights in both components. As a result, the common envelope must be treated as baroclinic rather than barotropic (Shu et al., 1979; Tassoul, 1992). Different vertical (i. e. perpendicular to the local equipotential surface) pressure stratifications in both components produce the horizontal pressure gradient, driving mass motions on a dynamical time scale. In the absence of the Coriolis force the resulting large scale flows are symmetric around the axis joining the centres of both stars (Webbink, 1977). However, for a flow velocity being a significant fraction of the sound velocity the Coriolis force cannot be neglected. The force acts outwards in the equatorial plane, deflects the flow towards one side of the

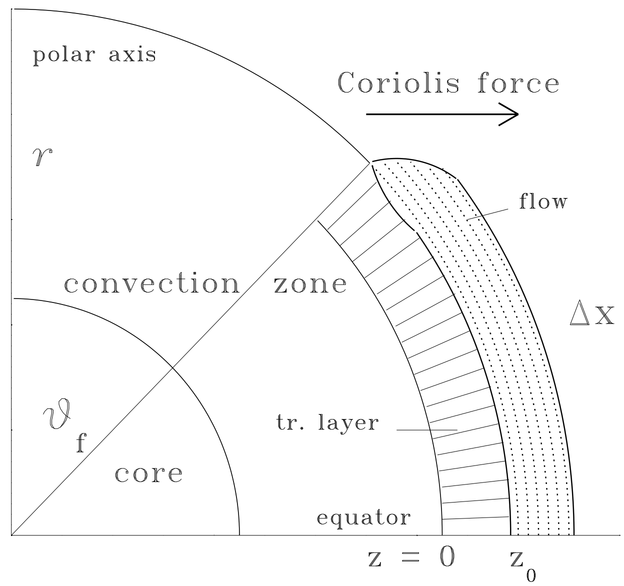

Figure 11: Geometry of the flow in the meridional plane of the secondary component. The stream flows away perpendicularly to the plane of the figure. The thickness of the flow and the transition layer are magnified for a better visibility.

neck between the components and makes it go around the other star in the direction of its orbital motion. The flow carries the mass from the primary and the energy which is radiated away during the flow around the secondary. Below, the main properties of the model developed by Stępień (2009) are presented.

To model the large scale flow the set of hydrodynamics equations has to be considered. A stationary solution was found neglecting viscosity and an inertial term in the equation of motion, which is small compared to the Coriolis term. The resulting equation describes the so–called geostrophic flow in which the meridional component of the Coriolis force balances the lateral pressure gradient, just as in the terrestrial atmosphere when the air circulates around a high or low pressure centre. The flow is driven by an azimuthal pressure gradient. A rough estimate shows that the flow velocity should be equal to the fraction of sound velocity, however, its accurate value needs numerical modelling of the flow. Instead of this, it was taken as a free parameter.

The stream carries hot matter coming from the primary. Such a configuration is stable against mixing, so the stream simply flows over the matter of the secondary. In a stationary state hot matter acts as a blanket preventing the energy produced in the core of the secondary to flow outside. A transition layer with a shallow temperature gradient develops between the bottom of the stream and the deep interior of the secondary's convection zone. As a result, the temperature is continuous along the radial coordinate and, of course, the hydrostatic equilibrium is preserved. The geometry of the flow is shown in Fig. 11.

Depending on the value of the flow velocity to the sound velocity, the resulting stream width varies from about $\pm 15°$ around the equator for the flow velocity equal to the sound velocity, and up to $\pm 90°$ for the velocity approaching zero. Its typical depth is of the order of a few percent of the primary's radius. As calculations show, the heat capacity of the flow matter is much larger than the energy radiated away when the secondary is encircled. The stream returning to the primary will be only slightly cooler than when it started its journey, and its temperature will be very close to the surface temperature of the primary. The estimate of the amount of mass carried by the stream gives a value of $10^{-3} - 10^{-4}\, M_{\odot}$/year. All that matter returns to the primary but a very small fluctuation

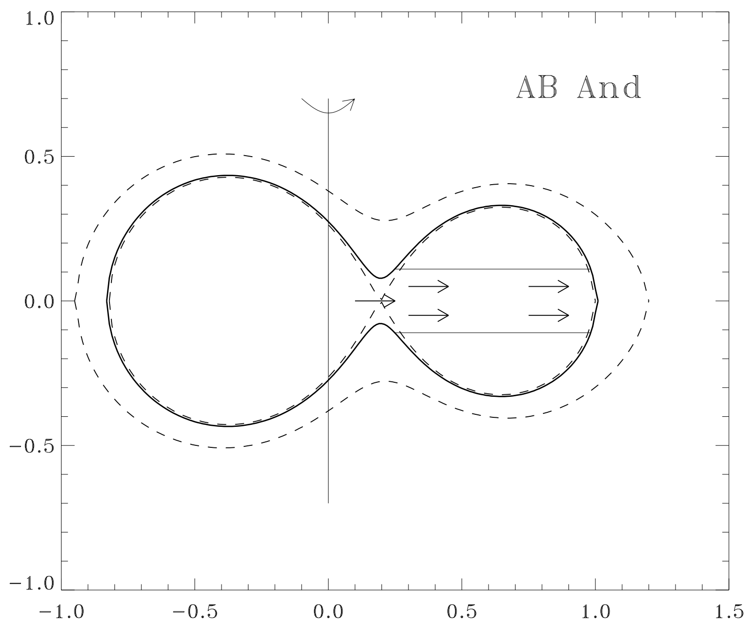

Figure 12: A side view of AB And with a stream covering 50% of the secondary's surface. Broken lines indicate the inner and outer critical surfaces and the solid line shows the binary surface.

of the mass flux is sufficient to cause period variations with the observed magnitude.

What is the reaction of each component to the existence of the flow? The stream blocks the energy flowing from the core of the secondary. The convection envelope of the secondary reacts by a slight increase of the specific entropy and the blocked energy is radiated away by the polar regions, not covered by the stream. The increase of entropy results in a small (of the order of a few percent) increase of the secondary's radius, and a reduction of the radiating area is exactly compensated in the stationary state by an increase in surface temperature of the polar regions. The surface averaged temperature can be calculated by a weighted average of the stream temperature and the temperature of the polar regions.

The primary experiences the stream as an additional energy sink. Its convection zone reacts by a slight lowering of the specific entropy followed by small radius decrease. The surface temperature is correspondingly lower than in the absence of the flow.

The model does not explain the "W phenomenon". Observationally it shows that in some W UMa–types stars the primary has a lower apparent surface–averaged brightness than the secondary.[1] To explain the phenomenon a usually invoked explanation can be applied. It assumes that the primary is covered with cool spots (or, in a more conservative version, it is covered with spots more strongly than the secondary).

Now we can apply the presented above model, supplemented with cool spots to a well known W UMa–type binary, AB And. It has the orbital period of $P_{\rm orb} = 0.33\,$d, component masses of $M_{\rm pr} = 1.04\,M_\odot$ and $M_{\rm sec} = 0.60\,M_\odot$, and volume radii $R_{\rm pr} = 1.02\,R_\odot$ and $R_{\rm sec} = 0.78\,R_\odot$ (Baran et al., 2004). The star has a relatively low fill–out factor $f = 0.05$ (Baran et al., 2004), which corresponds to about 1% of the primary star radius. We adopt this value as the stream depth and assume the flow velocity to be equal to 1/3 of the sound velocity at the bottom of the stream. The equatorial

[1] The primary in the nomenclature used here means an always more massive and larger component. Some observers use the term "primary" to describe the component with higher surface brightness, irrespective whether it is more or less massive.

flow with the velocity of 10 km/s covers in this case 50% of the secondary's surface (Fig. 12).

According to our model, the primary has the effective temperature of 5800 K resulting from the core luminosity, and the secondary has the effective temperature of 4570 K, assuming that its core is completely hydrogen–depleted. Because a half of its surface is covered with the stream, the temperature in the polar region must increase to 5340 K to radiate away the whole energy produced in the core. On the other hand, the stream cools the primary down, so its temperature drops to 5590 K. This is also the temperature of the flow. The mean effective temperature of the secondary, consisting of the weighted average of polar region temperature and the flow temperature is equal to 5480 K. The resulting difference $\Delta T = T_{\rm pr} - T_{\rm sec}$ is equal to +110 K. The observations show, however, that ΔT is equal to −360 K for AB And (Baran et al., 2004) which means that the star demonstrates the "W phenomenon". To explain this difference it is necessary to assume that about 30 − 40% of the primary's surface is covered with cool spots (Stępień, 2009) with a negligible coverage of the secondary. There are arguments that the primaries of the W UMa–type stars are more likely covered with persistent magnetic regions producing spots and X–ray emission in the coronal arches than the secondaries (Stępień et al., 2001).

6 Summary

A new evolutionary scenario is presented for the formation and evolution of cool contact binaries of W UMa type. They are defined as binaries with initial masses of both components below the mass limit for the existence of a subphotospheric convection zone. It is assumed that detached, cool binaries with short orbital periods of about 2 days and solar type primaries (i. e. with masses $\sim 0.9 - 1.3\,M_{\odot}$) are the progenitors of contact binaries. The assumption is in agreement with the current view about the origin of close binaries.

The binaries lose AM via the magnetised wind from both components. As it turns out, the time scale for the orbital evolution due to AML of such binaries is equal to several Gyr or more, depending (primarily) on the length of the initial orbital period. Such time scales are the same as the nuclear time scales for the MS evolution of primaries. As a result of this coincidence, the primary is evolutionary advanced (i. e. it is close to, or beyond the TAMS) when the orbit shrinks, due to AML, so that the critical Roche lobe descents onto its surface and the RLOF occurs resulting in the mass transfer to the secondary. It is assumed that the mass transfer continues through the thick common envelope phase until the mass ratio reversal. Such an mass exchange episode is similar to the one taking place in Algols, but it is different from that considered in the TRO model (Lucy, 1976; Flannery, 1976), where no mass ratio reversal is assumed. Depending on the amount of AM left in the system, a contact binary or a short period Algol–type binary is formed. The latter binary transforms into a contact configuration following the additional AML. The contact binary evolves towards the extreme mass ratio system due to an interplay between the evolutionary driven mass transfer from the secondary to the primary and AML rate via the magnetised wind.

The present evolutionary model is supplemented with the energy transfer mechanism between the components of the contact binary. It is argued that the lack of hydrostatic equilibrium in the common envelope of a binary results in large scale circulations flowing from the primary through the neck connecting both components and encircling the secondary. The stream is kept close to the equator by the Coriolis force. The core energy of the secondary is radiated by the polar regions, not covered with the flow. Sizes of both components deviate by a few percent from the values they would have as single stars.

References

Baran A., Zola S., Rucinski S. M., Kreiner J. M., Siwak M., Drozdz M., 2004, Acta Astron., 54, 195

Bilir S., Karataş Y., Demircan O., Eker Z., 2005, MNRAS, 357, 497
Bonnell I. A., 2001, ASP Conf. Ser., 200, 23
Boss A. P., 1993, in: Sahade J., McCluskey G. E., Kondo Y. (eds), "The Realm of Interacting Binary Stars", Kluwer, Dordrecht, p. 355
Eggen O. J., 1961, Royal Observatory Bulletins, 31, 101
Eggleton P. P., 1983, ApJ, 268, 368
Flannery B. P., 1976, ApJ, 205, 217
Gazeas K., Stępień K., 2008, MNRAS390, 1577
Guinan E. F., Bradstreet D. H., 1988, in: Dupree A. K., Lago M. T. V. T., "Formation and Evolution of Low Mass Stars", Kluwer, Dordrecht, p. 345
Hilditch R. W., Collier Cameron A., Hill G., Bell S. A., Harries T. J., 1997, MNRAS, 291, 749
Ibanoğlu C., Soydugan F., Soydugan E., Dervişoğlu A., 2006, MNRAS, 373, 435
Kaluzny J., Rucinski S. M., 1993, ASP Conf. Ser., 53, 164
Kopal Z., 1955, Annales d'Astrophysique, 18, 37
Kuiper G. P., 1941, ApJ, 93, 133
Li L., Han Z., Zhang F., 2005, MNRAS, 360, 272
Lucy L. B., 1968, ApJ, 151, 1123
Lucy L. B., 1976, ApJ, 205, 208
Mathieu R. D., 1994, Annu. Rev. Astron. Astrophys., 32, 435
Mochnacki S. W., 1981, ApJ, 245, 650
Müller G., Kempf P., 1903, ApJ, 17, 201
Paczyński B., Szczygiel D. M., Pilecki B., Pojmański G., 2006, MNRAS, 368, 1311
Pilecki B., 2010, PhD Thesis, Warsaw University
Pribulla T., Chochol D., Heckert P. A., Errico L., Vittone A. A., Parimucha S., Teodorani M., 2001, A&A, 371, 997
Rahunen T., 1983, A&A, 117, 235
Rasio F. A., 1995, ApJ, 444, L41
Robertson J. A., Eggleton P. P., 1977, MNRAS, 179, 359
Rucinski S. M., 1998, AJ, 116, 2998
Rucinski S. M., 2000, AJ, 120, 319
Rucinski S. M., 2007, MNRAS, 382, 393
Rucinski S. M., Lu W., 2000, MNRAS, 315, 587
Rucinski S. M., Paczyński B., 2002, IBVS, 5321
Russell H. N., 1912, ApJ, 36,133
Russell H. N., Fowler M., Borton M. C., 1917, ApJ,45, 306
Sarna M. J., Fedorova A. V., 1989, A&A, 208, 111
Shu F. H., Lubow S. H., Anderson L., 1979, ApJ, 229, 223
Stahler S. W., 1988, ApJ, 332, 804
Stępień K., 1994, A&A, 292, 191
Stępień K., 1995, MNRAS, 274, 1019
Stępień K., 2004, IAUS, 219, 967
Stępień K., 2006a, Acta Astron., 56, 199
Stępień K., 2006b, Acta Astron., 56, 347
Stępień K., 2009, MNRAS, 397, 857
Stępień K., Schmitt J. H. M. M., Voges W., 2001 A&A, 370, 157
Szymański M., Kubiak M., Udalski A., 2001, Acta Astron., 51, 259
Tassoul J.–L., 1992, ApJ, 389, 375
Vilhu O., Walter F. M., 1987, ApJ, 321, 958
Webbink R. F., 1976, ApJS, 32, 583
Webbink R. F., 1977, ApJ, 215, 851
Webbink R. F., 2003, ASP Conf. Ser., 293, 76
Wood B. E., Müller H.–R., Zank G. P., Linsky J. L., 2002, ApJ, 574, 412
Yakut K., Eggleton P. P., 2005, ApJ, 629, 1055