Formation and evolution of W Ursa Majoris stars: fallacies and corrections

Z. Eker,1,2⋆ O. Demircan2 and S. Bilir3
1TÜBİTAK National Observatory, Akdeniz University Campus, 07058 Antalya, Turkey
2Çanakkale Onsekiz Mart University, Faculty of Sciences and Arts, Ulupınar Astrophysical Observatory, 17100 Çanakkale, Turkey
3Istanbul University, Science Faculty, Department of Astronomy and Space Sciences, 34119 Istanbul, Turkey

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ABSTRACT
Period histograms of eclipsing binaries generated with data from the All-Sky Automated Survey cannot be interpreted only using orbital evolution. Eclipse probabilities, selection effects and space distributions in the solar neighbourhood should be considered before any interpretations are made. Depending upon the physical dimensions (the total mass and the period) of the progenitor stars and the efficiency of the angular momentum loss mechanism, a newly formed W Ursa Majoris type binary can be at any age up to several Gyr. Also, the evolution in the contact stage is controlled not only by angular momentum and mass loss but also by mass transfer between the component stars. Thus, the mean life of the contact stages should be about 1.6 Gyr. A different time-scale would cause inconsistencies.

Key words: stars: activity – binaries: general – stars: evolution – stars: formation.

1 INTRODUCTION
Low-mass contact binaries, popularly known as W Ursa Majoris (W UMa) stars, are eclipsing binary stars with equally deep eclipses. The observational data and the theory of W UMa type contact binaries (WCBs) were revised extensively by Mochnacki (1981), Vilhu (1981) and Rucinski (1982). According to Rucinski (1986), the mechanism that seems to be most promising to form WCBs involves orbital angular momentum loss (AML) and the resulting orbital decay of detached but synchronized close binaries. AML through magnetic braking (Schatzman 1959; Kraft 1967; Mestel 1968) became especially popular after the study of Skumanich (1972), which presented observational evidence of decaying rotation rates for single stars. Magnetic braking and tidal locking were considered as the main route forming WCBs from systems initially detached but with comparable periods (Huang 1966; Okamoto & Sato 1970; van’t Veer 1979; Vilhu & Rahunen 1980; Mestel 1984; Guinan & Bradstreet 1988; Maceroni & van’t Veer 1991; Stepien 1995; Demircan 1999). However, a small group of very young WCBs were found by Bilir et al. (2005). Such very young (<0.5 Gyr old) WCBs were probably formed right at the beginning of the main sequence or during pre-main-sequence contraction phase (Eker et al. 2006).

Debates on the formation mechanisms continue. Referring to the period histograms of eclipsing contact, eclipsing semidetached and eclipsing detached systems of data from the All-Sky Automated Survey (ASAS), Paczyński et al. (2006) have stated that ‘at this time the contact systems seem to appear out of nowhere’ because the numbers of eclipsing detached systems appear to be insufficient to produce the observed numbers of eclipsing contact systems. In contrast, the same period histograms from the ASAS data, and the kinematical ages of W UMa subgroups, which were given by Bilir et al. (2005), have been interpreted by Li et al. (2007). They claim that, after a pre-contact duration of 3.23 Gyr, WCBs must be formed from the detached progenitors with orbital periods mostly less than 2.24 d and that the duration of the contact stage is 5.68 Gyr. However, Bilir et al. (2005) have shown that both very young (age <1 Gyr) and old W UMa stars coexist.

The aim of this paper is to show that the period histograms of WCBs produced from the ASAS data, and the kinematical ages of W UMa subgroups formed by Bilir et al. (2005), according to orbital period ranges, are consistent with the classical view that most WCBs are formed from detached progenitors of comparable periods and that the mean duration of the contact stage is about 1.6 Gyr. Other scenarios with different lifetimes would be inconsistent and/or fallacious.

2 DISCUSSION
2.1 Interpretation of the period histograms of the ASAS data
The ASAS is a long-term project, having three phases of operation dedicated to detecting and monitoring bright stars (V ≤ 14 mag; Paczyński et al. 2006). Using a single instrument with an aperture of 7 cm, a focal length of 20 cm, a standard V-band filter and a 2K × 2K CCD camera, in phase III 50 099 variable stars were distinguished. Among these, 11 076 eclipsing binaries were identified, and period histograms were produced of 5384 eclipsing contact (EC), 2949 eclipsing semidetached (ESD) and 2743 eclipsing detached (ED) binaries. Studying the period histograms of EC, ESD and ED...
binaries with $|b| > 30^\circ$, Paczyński et al. (2006) have concluded that there are comparable numbers of contact and semidetached systems but the relative numbers of detached systems are inconsistently small. It is as if observational data do not support the formation of W UMa stars from the detached systems of comparable orbital periods.

Relying on the same data, Li et al. (2007) argue that the ASAS data support the view of formation from progenitors with orbital periods less than $P = 2.24 \, \text{d}$, via AML driven by magnetic stellar winds. The peak value of $P = 2.24 \, \text{d}$ of the period distribution of ED systems is now old and invalid. Part of their evidence was the estimated tidal locking limit of $P = 2.4 \, \text{d}$. Moreover, fig. 1 of Li et al. (2007) appears to have been altered without any explanation, because the relative numbers of ED systems with respect to EC and ESD systems are not the same as in fig. 6 of Paczyński et al. (2006). By comparing orbital and rotation periods, Demircan et al. (2006) estimated that the tidal locking limit is no less than about 70 among the field of chromospherically active binaries (CABs) and around 10 d in the younger group of CABs.

Furthermore, it is incorrect to explain the peak value of the diagram via tidal locking. Not only the peaks, but also the shapes of the period distributions of EC, ESD and ED systems in the ASAS data should be explained through the combined causes of eclipse probability and selection effects.

### 2.2 Interpretation of kinematical age versus mean mass and period

Being unaware of serious inconsistencies, Li et al. (2007) established a theory of W UMa formation based only on the fact that the period distribution peak ($P = 2.24 \, \text{d}$) of the ASAS data of ED binaries was found to have a value close to that of the old estimate of the tidal locking limit of van’t Veer & Macroni (1988). Similarly, because there is a 2.33 Gyr decaying time for a typical ED to form a typical ESD binary using the rates of Demircan et al. (2006), which is close to the kinematical age of the youngest subgroup (3.21 Gyr) of Bilir et al. (2005). Li et al. (2007) claimed that W UMa binaries must have been formed after a pre-contact stage with a maximum of 3.23 Gyr. Moreover, because the age difference between the youngest and oldest groups in Bilir et al. (2005) is 5.68 Gyr, Li et al. (2007) adopted 5.68 Gyr as the mean lifetime of W UMa stars. Consequently, the mean lifetime (5.68 Gyr) and typical pre-contact duration (3.23 Gyr) require that the mean kinematical ages of the oldest W UMa stars are 8.91 Gyr. The inconsistency is clear because the kinematical data of Bilir et al. (2005), from which the theory of Li et al. (2007) was established, are known to produce 5.47 Gyr for the mean kinematical age of the field W UMa stars. However, the theory of Li et al. (2007) overestimates the mean kinematical ages as $8.91 \, \text{(oldest)} + 3.23 \, \text{(youngest)} / 2 + 3.23 = 6.07 \, \text{Gyr}$.

Moreover, such a theory appears to be established under the misconception that all stars in different age groups have similar ages, which is not true. It is possible that the oldest group may contain a W UMa star just formed at an age of 3.23 Gyr, while the youngest group may contain a W UMa star that is about 9 Gyr old. Finally, the theory of Li et al. (2007) fails to explain very young (age $< 0.6 \, \text{Gyr}$) W UMa stars, which has been discussed by Bilir et al. (2005).

The adoption of the 5.68-Gyr lifetime for WCBs by Li et al. (2007) implies the following scenario. A detached binary, which is eligible to form a WCB, must join the youngest group after 3.21 Gyr of a detached pre-contact phase. Then, being a typical WCB, it must continue secular evolution sequentially joining all the groups one by one. After the oldest group it ends as a fast rotating single star. The youngest group with the longest periods mostly contains WCBs of spectral types A or early F. Gradually, the dominant spectral type changes to K type for the oldest group. This is a scenario that claims that main-sequence stars evolve from O type to M type by losing heat, mass and AM without leaving the main sequence, which is inconsistent and false according to contemporary astrophysics and stellar evolution.

The appearance of some diagrams, such as Hertzsprung–Russell (HR) and angular momentum–$P$ (period) diagrams, could be misleading. Independent evidence must be found for the direction of the evolution. For the HR diagram, independent evidence comes from the internal structure and evolution models. These predict that the direction of the evolution is from the main sequence towards the red giant or supergiant region. The method of Demircan et al. (2006) provides the direction and amount of dynamical evolution of CAB stars independently. However, the same method cannot be used for WCBs (Eker et al. 2007), because the pre-contact detached duration varies. As predicted from the theory of tidal locking and magnetic braking via magnetic stellar winds, the pre-contact stage could take any amount of time within the main-sequence lifetime (Guinan & Bradstreet 1988; van’t Veer & Macroni 1988; Stepen 1995), depending on the initial periods and masses of the progenitors. This means that a detached binary, if it is eligible, may join any of the field W UMa subgroups of Bilir et al. (2005) by losing mass and orbital angular momentum when its age is within the range from zero to several Gyr, as suggested by the initial conditions of the binary orbit and the rate of AML.

Bilir et al. (2005) also noted that the field W UMa subgroups are not only populated by systems dynamically evolving from a younger subgroup to an older subgroup; a system of any age that has just become a WCB, may join any group unexpectedly. If we fit a linear variation of the angular momentum, $P$ or $M$, according to the mean kinematical ages of WCB subgroups, we may find a rate mathematically that would be meaningless physically. Note that this is not the case for CAB stars as there are no progenitors surrounding pre-CAB stars.

The correct method for deducing the dynamical evolution for WCBs on an angular momentum–total mass diagram is still not known. The method of Li et al. (2007) would appear to be wrong, because the masses and periods of W UMa stars are not arbitrary, as in the case of detached systems. There could be detached systems all having the same orbital period but their systemic masses may vary from half a solar mass to tens of solar masses. This is not the case for WCBs, as the mass contained in Roche lobes is limited; changing the mass requires changing the orbital period and then the angular momentum of the system will change accordingly. Consequently, it is pointless to use kinematical ages to estimate $\text{d}J / \text{d}M$ in order to indicate the true dynamical evolution, as $J$ (systemic angular momentum) and $M$ are not arbitrary and time dependence is cancelled when computing $\text{d}J / \text{d}M$. More importantly, angular momentum evolution of WCBs is not only a result of AML through magnetic stellar winds, but mass transfer between the components also plays a dominant role, which is not easy to handle but still must be considered in the evolution of WCBs.

## 3 CONCLUSIONS

(i) It is possible to model the period histogram of binaries from the ASAS data theoretically. Such a model would contain mostly the eclipse probabilities and observational selection effects, together with an estimated true number density distribution of binaries with different masses and orbital periods. Such a model would also be
useful to estimate the true distribution, which could be useful for studying the origins of binaries.

(ii) WCBs can be formed at any age depending upon the physical conditions of their progenitors, such as their periods, component masses and the efficiency of the AML mechanism. Therefore, grouping these into various ages does not indicate that the younger group is the progenitor of the older group of stars. If there is equilibrium in the population of WCBs, and if they are mostly formed from detached CAB systems, the kinematical age of field WCBs (5.47 Gyr; Bilir et al. 2005) and the kinematical age of CAB systems (3.86 Gyr Karataş et al. 2004) indicate that the mean lifetime of the contact stage is about 1.61 Gyr, as in the pool problems. Otherwise, a different lifetime would be inconsistent with existing kinematical data.

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