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The effect of activity on the fundamental properties of low-mass stars

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Abstract

The analyses of eclipsing binary systems unveiled differences between the observed radii and effective temperatures of low-mass stars and those predicted by stellar models. These discrepancies have been attributed to different factors, notably to the high levels of magnetic activity present on these stars. We have tested the effect of these activity both on models and observations and we conclude that spots have a significant effect on the determination of the radii of the stars as well as on its evolution. Assuming the existence of polar spots, agreement between models and observations is found for a spot coverage of $\sim 35\%$ of the stellar surface, that can cause a systematic deviation on the determination of the stellar radius of $\sim 3\%$. In addition, the reduction of the convective transport efficiency on fast rotating stars may explain another $\sim 4\%$ radius discrepancy.

1 Introduction

In past years, analyses of double-lined eclipsing binaries (hereafter DLEBs) have provided fundamental properties, such as masses and radii, for low-mass stars ($M < 1$ M$_\odot$) with accuracies well below the $\sim 1\%$ limit, revealing these systems as especially valuable to test stellar structure models. Results coming from such tests using DLEBs indicate that stellar structure models underestimate the radii of the components by $\sim 5-10\%$ and overestimate their effective temperatures by about 5%, while, in contrast, luminosities are correctly predicted (see [15] for a review). These discrepancies are not only observed for DLEBs but also between magnetically active and non-active single Main Sequence low-mass stars [9], thus supporting the hypothesis that magnetic activity could be the cause of the differences between models and observations as suggested by several authors [19, 7, 20, 6, 16]. Activity effects are notably important on DLEBs since their orbits are close enough to force the components to spin up in orbital synchronization [8]. Therefore, they are fast rotators that in the presence of magnetic fields trigger high activity levels.

Corrections on stellar structure models were proposed to account for the effects of activity on the fundamental properties of low-mass stars [3]. In this work, the authors suggest that magnetic activity can affect the stellar structure both by inhibiting the convective motions, which they model varying the mixing length parameter α, or by the appearance of photospheric spots that block part of the out-going flux, which they model with a new parameter β as $L \propto (1-\beta)\, R^2\, T_{\rm eff}^4$, where L, R and $T_{\rm eff}$ are the luminosity, radius and effective temperature of the star. Their results show that both scenarios predict larger radius than standard stellar models [1], but while the effect of spots is significant over the entire low-mass domain, the effect on convection is relatively smaller for fully convective stars ($M \leq 0.4$ M$_\odot$).

Here, we summarize our analysis of the magnetic activity effects both on stellar models and on observations [12] in order to test the spot coverage needed by stellar models to reproduce the observations.

2 Effect of spots on DLEBs

The total luminosity of a spotted star is the contribution of the spotted surface, $S_{\rm s}$, at an effective temperature $T_{\rm eff,s}$ and the immaculate surface at an effective temperature $T_{\rm eff}$. This indicates that the β factor introduced in stellar models can be written as

$$\beta = \frac{S_{\rm s}}{S}\left[1 - \left(\frac{T_{\rm eff,s}}{T_{\rm eff}}\right)^4\right], \tag{1}$$

where S is the total surface of the star. For dark spots ($T_{\rm eff,s} = 0$), β is a measure of the surface covered by spots as defined in stellar models [3]. However, in the realistic case, spots are not completely dark and β is a lower limit of the fraction of spots. Thus, a dark spot coverage between 30% and 50% as those suggested to reconcile models with observations [3], translates to a real spot coverage between 65% and 100% for low-mass stars with spots few hundreds of kelvin cooler than the photosphere.

In order to test these large values of spot coverages on DLEBs, we developed a code to randomly place spots on the surfaces of the stars of a DLEB with different β values and we computed its light curve using the Wilson-Devinney code (hereafter WD, [22]). We assumed a uniform longitude distribution and tried different distributions over latitude as indicated by theoretical works [5]. The left panel of Fig. 1 shows the density distributions over latitude of the spots. Two distributions were adapted from the literature [5], being Distribution 2 more concentrated toward the stellar poles than Distribution 1, and a uniform distribution was also tested for comparison. The simulated light curves were used to estimate the amplitude of the modulations induced by spots and also to check for possible systematic effects by fitting 33 of these curves using again the WD code (see [12] for further details).

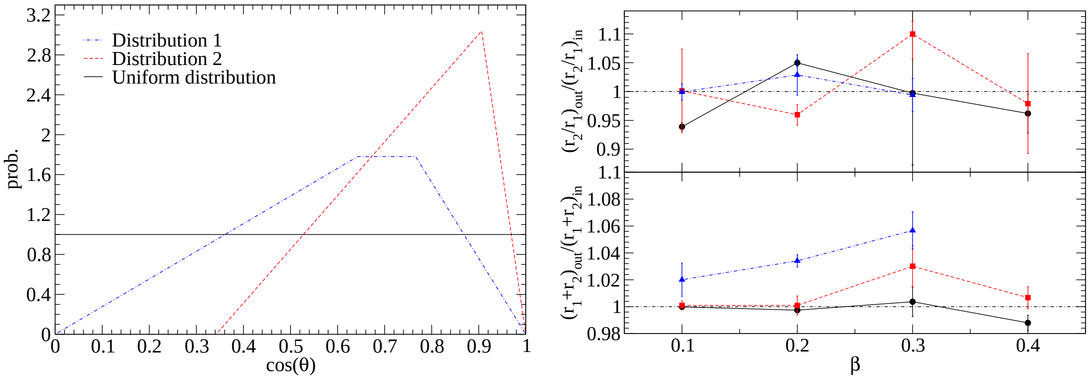

Figure 1: *Left*: Probability density functions over $\cos\theta$ used to simulate the location of spots on stars. $\theta = 90^\circ$ corresponds to the equator of the star. *Right*: Ratios between the input parameters and those recovered from the fits. Same legend as left panel.

The results indicate that all of these distributions can reproduce the observed amplitude of the modulations of spots specially when taking into account that this amplitude depends on the thermal properties and the size of the spots. On the other hand, when these simulated light curves were fitted as if they were real observations, any of the relevant parameters were significantly affected except for the sum of radii. The right panel of Fig. 1 shows the sum and the ratio of radii relative to the input value of the simulations. It is clear from this figure that spots distributed preferentially over the poles cause a systematic increase of the sum of radii, and hence the individual radii, that can reach up to 6%. For distributions less concentrated to the poles, the differences seem to be random. Therefore, if polar spots are present in low-mass DLEBs, as observed on other stars by Doppler imaging techniques [18], they could be responsible for up to $\sim 6\%$ of the discrepancy between models and observations depending on the spot coverage.

3 Comparison with stellar models of active stars

As already mentioned in Section 1, activity can be introduced in the models both reducing the mixing length parameter α or including a spot parameter β. CM Dra [11] offers the best opportunity to discern between the effects of both of these parameters, because its components are fully convective, so their structure is almost independent of the mixing length parameter. Thus, we used the components of CM Dra to estimate the β value that best fit the observations assuming the presence of polar spots. We compared the theoretical $M - R$ relationships, interpolating between models with different β and we compared with the observational values corrected for the systematic effect of polar spots according to the results shown on the right panel of Fig. 1. After iterating the process, the best fit for the case of CM Dra is found for a model with $\beta = 0.17 \pm 0.03$ that reproduces the radii of both components when they are downward corrected by $\sim 3\%$. If spots are $\sim 15\%$ cooler than the photosphere this β value corresponds to $(36 \pm 6)\%$ of the surface of the star covered with

Table 1: Masses and radii for the best known DLEBs.

EB	Comp.	P (days)	M_* ($M_\odot$)	R_* ($R_\odot$)	$T_{\rm eff}$ (K)	Ref.
V818 Tau:	B	5.61	0.7605±0.0062	0.768±0.010	4220±150	[19]
IM Vir:	B	1.31	0.6644±0.0048	0.681±0.013	4250±130	[10]
NGC2204-S892:	A	0.45	0.733±0.005	0.720±0.010	4200±100	[17]
	B		0.662±0.005	0.680±0.020	3940±110	
GU Boo:	A	0.49	0.6101±0.0064	0.627±0.016	3920±130	[21]
	B		0.5995±0.0064	0.624±0.020	3810±130	
YY Gem:	A&B	0.81	0.5992±0.0047	0.6191±0.0057	3820±100	[21]
CU Cnc[a]:	A	2.77	0.4349±0.0012	0.4323±0.0055	3160±150	[21]
	B		0.3992±0.0009	0.3916±0.0094	3125±150	
CM Dra:	A	1.27	0.2310±0.0009	0.2534±0.0019	3130±70	[21]
	B		0.2141±0.0008	0.2398±0.0018	3120±70	

[a] $T_{\rm eff}$ could be underestimated due to the presence of circumbinary dust.

spots. This value is in agreement with findings from Doppler imaging for some stars [2].

In order to extend this analysis to more massive systems, we considered the DLEBs with fundamental properties derived with accuracies better than 3% listed in Table 1. It is already known that the DLEBs with periods below ~ 10 days, have saturated levels of magnetic activity due to their fast rotation [13]. Thus, we assumed that all of the DLEBs in the saturated regime have the same β value as CM Dra, therefore, if their spots are also polar, their radii should have to be corrected by the 3% systematic effect.

Top panels of Fig. 2 compares the $M-R$ theoretical relationships with different values of β and α with the observational radii of the best known DLEBs corrected for the 3% systematic effect and normalized to and age of 1 Gyr according to the standard Lyon stellar models [1]. These plots show the good agreement between models and observations when the effect of spots is considered both on observations and on models, assuming $\beta = 0.17$, while, as expected the models with different α values do not reproduce the less massive systems. Interestingly, bottom panels of Fig. 2 show that the model with $\beta = 0.17$ also reproduces the effective temperatures of the systems, with the exceptions of CU Cnc, that may be affected by the presence of circumstellar dust disk [14], and IM Vir, possibly due to its subsolar metallicity [10].

Nevertheless, some remaining differences are still apparent when comparing observations with the $\beta = 0.17$ model for systems such as YY Gem and GU Boo. However, these are the fastest rotating systems, thus this additional discrepancy may be an indication of an additional effect of rotation and/or magnetic activity that can cause a reduction of the convective transport efficiency. Therefore, for these systems, both the effect on α and β should have to be taken into account to reconcile models and observations.

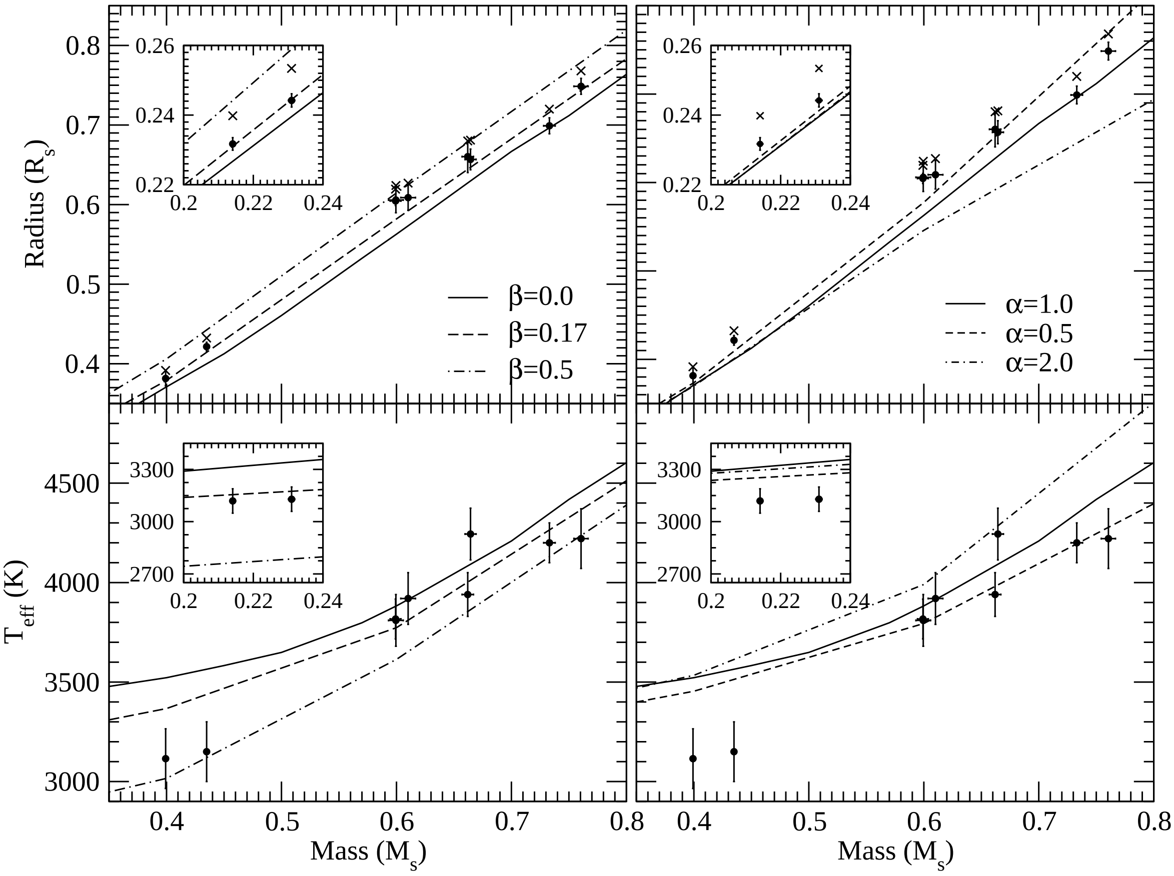

Figure 2: Comparison between models and observations for the DLEBs listed in Table 1 for different values of α and β. *Top*: $M - R$ relationship. Filled symbols with error bars are the observational radii normalized to an age of 1 Gyr and corrected for the 3% systematic effect due to polar spots. *Bottom*: $M - T_{\text{eff}}$ relationship. The insets display the case of CM Dra.

4 Conclusions

The results of our analysis show that no single effect can account for the whole discrepancy between models and observations. Our tests indicate that in order to explain the $\sim$ 5%–10% radius discrepancy in low-mass DLEB stars three factors have to be considered. First, a systematic effect due to presence of polar spots that amounts for $\sim$ 3%; second, an increase of the stellar radii due to the reduction of radiative efficiency because of the presence of spots that can be modelled with a $\beta \sim 0.17$ and explains 2% of the radius difference; and finally, an increase of the radius due to the loss in convective efficiency in fast rotating stars that can be reproduced reducing the mixing length parameter α and that would account for up to 4% of the radius discrepancy for partially convective stars.

This analysis clearly indicates that activity plays an important role on the stellar structure and evolution of low-mass stars. Accurate fundamental properties of new DLEBs from missions such as CoRoT or Kepler will improve the statistics and better define the scenario to explain the differences between models and observations. Interestingly, recent results comparing the fundamental properties of low-mass DLEBs with different orbital periods (i.e. different activity levels) show that inactive systems are better described by models [4], thus confirming that the discrepancies are due to the effect of activity.

Acknowledgments

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