Low-Mass Stars as Tests for Stellar Models

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Abstract Low-mass eclipsing binaries have unveiled that stellar models do not reproduce the radii and effective temperatures of its components while luminosities are correctly predicted. The magnetic activity due to the rapid rotation of these stars has been proposed as the cause of these differences between models and observations and corrections to the models have already been suggested. One of the theoretical scenarios is considering that stars could be more spotted than it is deduced from light curves. Therefore, tests to the amount of spot coverage needed in the models to reproduce observations are implemented on well-known eclipsing binary systems and consistency checks between these corrections and observations are presented.

1 Introduction

Analyses of double-lined eclipsing binaries (hereafter DLEBs) have provided in past years fundamental properties, such as masses and radii, for stars with accuracies below the ∼1% limit which are suitable to test stellar evolutionary models.

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In the low-mass stars domain ($M < 1$ M$_\odot$), such tests using DLEBs have revealed that stellar structure models underestimate the radii of the components by $\sim$10% and overestimate their effective temperatures by $\sim$5%. In contrast, luminosities are correctly predicted [13]. Similar discrepancies are also found between magnetically active and non-active single Main Sequence low-mass stars [9], indicating that magnetic activity may play an important role on these low-mass stars [14].

Activity effects are specially important on these DLEBs since their orbits are close enough to force the components to spin up in orbital synchronization [8]. Therefore, they are fast rotators which in the presence of magnetic fields display high activity levels.

Recently, corrections on stellar structure models have been proposed to account for the discrepancies between models and observations [3]. Here, we present an analysis of these corrections using the best-known low-mass binaries as well as a consistency check to study the compatibility of these corrections with the observational data from DLEBs.

2 Activity effects on models

Magnetic activity on low-mass stars is considered to affect the stellar structure both inhibiting the convective motions and producing surface features such as spots [3]. The first effect could be introduced in stellar models by reducing the $\alpha_{\rm ML}$ parameter of the mixing length theory of convective energy transport. The spot scenario is mimicked including a new parameter β which measures the amount of outgoing flux blocked by spots defined as:

$$L' = (1-\beta)\,4\pi\sigma R'^2 T'^4_{\rm eff} \quad (1)$$

where L', R' and $T'_{\rm eff}$ are the luminosity, the radius and the effective temperature of the spotted star, respectively.

Tests over these two parameters revealed that reducing the values of the mixing length parameter $\alpha_{\rm ML}$ on models, greater radius are predicted for stars above the fully convective boundary ($M < 0.3$ M$_\odot$), while for stars below this limit corrections are not significant. In the case of the β parameter, the effect of the presence of spots blocking the outgoing flux is to increase the radius of the star to conserve the stellar flux and, therefore, the effective temperature is diminished.

These results, point out that both effects could reproduce the difference between observations and models. However, since the effect is different depending on the mass range, i.e., the effect of $\alpha_{\rm ML}$ is not significant on fully convective stars, both mass domains were analyzed separately. Therefore we used the best-known DLEBs listed in Table 1 to test the models comparing the stars below and above 0.3 M$_\odot$ with stellar evolutionary models [1] with different sets of $\alpha_{\rm ML}$ and β parameters.

On Fig. 1, the case of the fully convective DLEB system CM Dra is shown compared with different models as labeled. It can be seen that with a spot blocking factor

Table 1 Masses and radii for the best known DLEBs.

EB	P (days)	M_* ($M_\odot$)	R_* ($R_\odot$)	Ref.
2MASS J05162881+2607387 A	2.59	0.787±0.012	0.788±0.015	[2]
2MASS J05162881+2607387 B		0.770±0.009	0.817±0.010	
V818 Tau B	5.61	0.7605±0.0062	0.768±0.010	[15]
RXJ0239.1-1028 A	2.07	0.730±0.009	0.741±0.018	[7]
RXJ0239.1-1028 B		0.693±0.006	0.703±0.016	
GU Boo A	0.49	0.610±0.007	0.623±0.016	[6]
GU Boo B		0.599±0.006	0.620±0.020	
YY Gem A & B	0.81	0.5992±0.0047	0.6191±0.0057	[15]
CU Cnc A	2.77	0.4333±0.0017	0.4317±0.0052	[12]
CU Cnc B		0.3890±0.0014	0.3908±0.0094	
CM Dra A	1.27	0.2310±0.0009	0.2534±0.0019	[10]
CM Dra B		0.2141±0.0010	0.2396±0.0015	

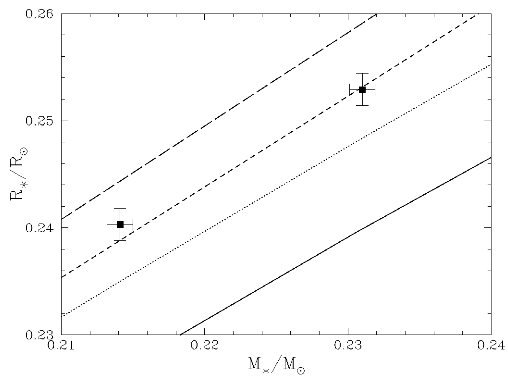

Fig. 1 Theoretical M_*-R_* relationship for fully convective stars compared with the observational properties of CM Dra. Standard stellar models with $\alpha_{\rm ML} = 1$ are shown for $\beta = 0$ (solid line), $\beta = 0.3$ (dotted line), $\beta = 0.4$ (short-dashed line) and $\beta = 0.5$ (long-dashed line).

of about 40% (β =0.4), models reproduce both components of the system within the errors assuming $\alpha_{\rm ML}$ =1.0. Tests over $\alpha_{\rm ML}$ did not produce significant corrections on the radius of the the components of this system.

For upper-late main sequence stars with radiative cores, we performed tests both on $\alpha_{\rm ML}$ and β. In this mass range lower values of $\alpha_{\rm ML}$ predict significantly larger radii of stars with corrections that decrease towards lower masses. In Fig. 2, it can be seen that all the systems are reproduced with $\alpha_{\rm ML}$ values between 1.5 and 1.9, which are similar to that used for the Sun ($\alpha_{\rm ML}$ =1.9), and with $\beta = 0.4$. This result seems to indicate that low-mass stars have the same level of spot activity regardless of their mass. However, it should also be noticed that Zeeman-Doppler Imaging techniques revealed systematic different magnetic topologies between fully and partially convective stars [4, 11].

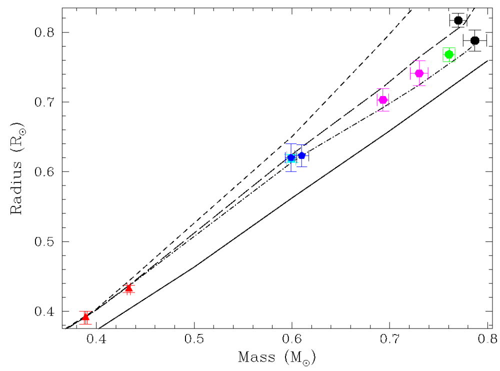

Fig. 2 Theoretical M_*-R_* relationships for low-mass stars with radiative cores compared with the observational properties of the systems given in Table 1. A standard stellar model with $\alpha_{\rm ML} = 1$ and $\beta = 0$ is shown as comparison along with models with $\beta = 0.4$ and $\alpha_{\rm ML} = 0.5$ (short-dashed line), $\alpha_{\rm ML} = 1.0$ (long-dashed line) and $\alpha_{\rm ML} = 1.9$ (dot-dashed line).

3 Simulation of spots on eclipsing binaries

Eclipsing binary light curves of low-mass stars usually display a modulation on the out-of-eclipse phases which is a signature of the presence of spots on the surface of its components. From the shape of these modulations, properties such as the size and the temperature of spots relative to the effective temperature of the star could be estimated using eclipsing binary analysis codes such as the Wilson-Devinney code (hereafter WD, [16]). These properties could provide estimates of β according to:

$$\beta = \frac{S_{\rm s}}{S_*}\left[1 - \left(\frac{T_{\rm s}}{T_{{\rm eff},*}}\right)^4\right] \tag{2}$$

where S_* and $S_{\rm s}$ are the surface of the star and the portion which is spotted, respectively, and $T_{{\rm eff},*}$ and $T_{\rm s}$ are the effective temperature of the photosphere and the spots, respectively.

Several of the DLEBs listed on Table 1, such as YY Gem, GU Boo and CM Dra, have light curves from which properties of spots were obtained and from which β values below 0.1 are recovered. This seems to be in contradiction with the theoretically predicted value of β =0.4, however modulation on light curves do not provide the absolute surface covered by spots but only inhomogeneities over the orbital phase. For instance, a star with one spot would show similar modulations as another with the same spot and an spotted belt. The overall light of the light curves would be diminished but since differential magnitudes are used, the presence of the spotted belt would not be induced from light curves.

Therefore we can assume $\beta = 0.4$ and simulate light curves to check if the amplitude of the modulations produced by this spot coverage is compatible with that found for DLEBs. To do this, we simulated stars with spots ~ 500 K cooler than the photosphere. Assuming this value of temperature factor, and selecting a β value, the total surface covered by spots could be computed according to Eq. 2. Subsequently, we randomly allocated spots of 10 deg over the surface of the star and used the WD code to compute the light curve of a binary system with such spotted compo-

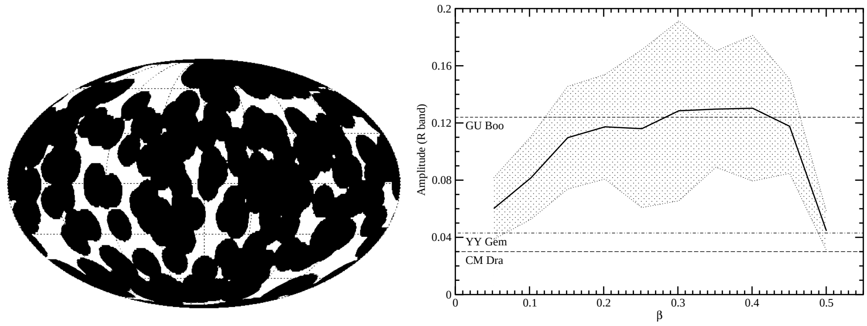

Fig. 3 Left: simulated surface of a star (in Mollweide projection) randomly spotted up to $\beta = 0.4$. Right: mean value of the amplitude on the out-of-eclipse phases for the light curves simulated with different β values. Shady region shows the standard deviation of the amplitudes.

nents. Peak-to-peak modulations due to spots were then computed comparing with the unspotted light curve. A total number of 25 simulations were performed for each β value to compute mean average amplitudes and dispersions.

On Fig. 3, the appearance of one of such simulated spotted stars is shown as well as the amplitude of the modulation of light curves in the R band for different β values for simulations over a star like YY Gem. Observational values found for YY Gem, CM Dra and GU Boo are also shown for comparison. It can be seen that a spot coverage of about 0.4 could recover the observational values of the modulation for GU Boo while YY Gem and CM Dra have lower amplitude modulations. However, distribution of spots over the surface of these stars evolves with time, therefore the amplitude of the modulation due to spots could vary from epoch to epoch as has been observed for the case of YY Gem [15] for which amplitudes on the V band of $\sim$0.05 and $\sim$0.09 are reported for different epochs. Besides, the amplitude of the modulations on the out-of-eclipses phases is dependent on the size, the temperature contrast and the distribution of spots. In this work, we tested a uniform distribution of spots over latitude and longitude of stars, however, some analyses have revealed the existence of a relation between the distribution of spots and the mass and rotation of the star [5]. Research is underway to test the effect of different configurations of spots on light curves.

4 General conclusions and future prospects

Recent corrections on stellar evolutionary models of low-mass stars [3] have been tested on the best-known eclipsing binary systems. All the analyzed systems could be fitted with a spot flux blocking factor of β =0.4 and common values of the mixing length parameter. This indicates that the presence of spots may be the dominant effect in modifying the properties of magnetically active stars with respect to inactive stars.

Moreover, simulations of randomly spotted stars have demonstrated that a spot coverage surface factor of about 0.4 is compatible with the modulation observed in the out-of-eclipse phases of DLEBs. However, research to analyse the dependence of the modulation produced by spots and the properties and distribution of spots is underway.

The theoretical β value of 0.4 found here for these DLEBs, according to the effective temperature of these stars ($\sim$3000 K) and the temperature considered for spots ($\sim$500 K cooler than photosphere), means that approximately 80% of the star would be covered by spots. However, this rather high coverage of spots is strongly dependent on the temperature of spots. Recent analysis of Doppler imaging and surface mapping using planetary transits on low-mass stars could provide further check to the properties of star spots and the total surface covered by spots deduced here from models.

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