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Fundamental properties of low-mass stars

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Abstract. Numerous investigations on the fundamental properties of low-mass stars using eclipsing binaries indicate a strong discrepancy between theory and observations that is still awaiting explanation. Current models seem to predict radii for stars less massive than the Sun that are some 10% smaller than observed, while their effective temperatures are some 5% larger. Here we discuss recent new observational data that are relevant to this issue and review the progress made in understanding the origin of the important differences with theoretical calculations. Notably, we provide evidence that stellar activity may be responsible for the mismatch between observations and theory through two different channels: inhibition of convection or effects of a significant starspot coverage. The activity hypothesis is put to a test with observational diagnostics and some of the consequences of the large starspot coverage are evaluated. We conclude that stellar activity likely plays a key role in defining the properties of active low-mass stars and that this should be properly taken into account when investigating young, active stars in clusters or star-forming regions.

Key words. Stars: activity – Stars: fundamental parameters – Stars: late-type – Binaries: eclipsing

1. Introduction

Evidence collected over the past years convincingly shows that the components of low-mass eclipsing binary stars are not adequately reproduced by current evolution models. The observations yield stars that are systematically larger and cooler than theoretical calculations by about 10% and 5%, respectively. But, in contrast, these binary components are found to have luminosities that are in good agreement with those of single stars and also with model predictions. This is the reason why studies focused solely on the mass-luminosity relationship did not reveal any mismatch between observations and theory and, further, obtained very tight mass and luminosity correspondence when using infrared photometry (e.g., Delfosse et al. 2000).

A revision of the available observational evidence and some hints about the possible resolutions of the discrepancies were provided by

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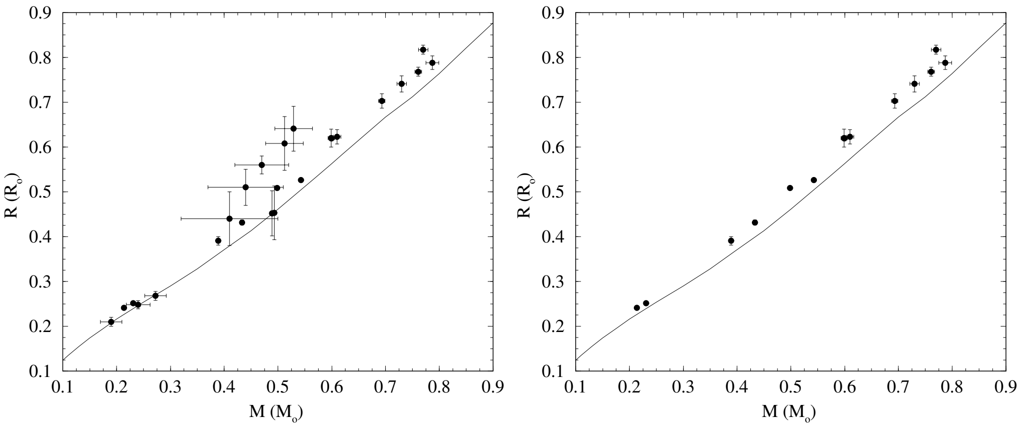

Fig. 1. Left: *M–R* plot for low-mass eclipsing binary stars with empirical determinations. Right: Same but for stars with uncertainties below 3%. The solid line represents a theoretical isochrone of 1 Gyr calculated with the Baraffe et al. (1998) models.

Ribas (2006). We refer to that study for background information and detailed references. Here we shall only discuss new results appeared since 2006 and also the progress made in understanding the origin of the difference between model predictions and observations of fundamental properties of low-mass stars.

2. Recent observational data

New low-mass eclipsing binaries have resulted in the past two years from dedicated monitoring of carefully selected targets from photometric databases of variability surveys. These have been published by López-Morales & Shaw (2006) and López-Morales et al. (2006). In addition, the low-mass eclipsing binary reported by Hebb et al. (2006) resulted from a deep targeted search in several open clusters. In other cases, low-mass eclipsing binaries were serendipitously discovered over the course of photometric monitoring campaigns with different scientific aims, and later analyzed specifically in detail, such as the objects studied by Bayless & Orosz (2006), Young et al. (2006), and Blake et al. (2007). A mass-radius plot of all presently known low-mass stars in detached eclipsing binaries is provided in Fig. 1 (left), while Fig. 1 (right) shows only those objects that have reported error bars in both masses and radii below 3%. The systematic offset of 5–10% between the observations and the 1 Gyr isochrone from the models of Baraffe et al. (1998) is apparent.

In addition to the "classical" eclipsing binaries, there has been an increasing number of discoveries resulting from follow-up of planetary transit candidates. In some instances, the object responsible for the transit was found not to be a planet but an M-dwarf secondary to a F-G-type primary star. This is the case of the recent study by Beatty et al. (2007) of one of the HAT network planetary candidates. These objects are single-line and single-eclipse binaries that directly provide a value of the stellar density but that require certain assumptions (e.g., orbital synchronization) to derive the actual masses and radii. A similar technique exploited by Torres (2007) has provided masses and radii (dependent on the assumed effective temperature) for the M-type star GJ 436, which hosts a transiting exoplanet. A mass-radius plot of all the objects resulting from single-line radial velocities and single-eclipse light curves is shown in Fig. 2. The only object in this sample with an error bar below 3% (making it a reliable test of models) is GJ 436. Interestingly, it also shows the 10% radius differential with model predictions (Torres 2007).

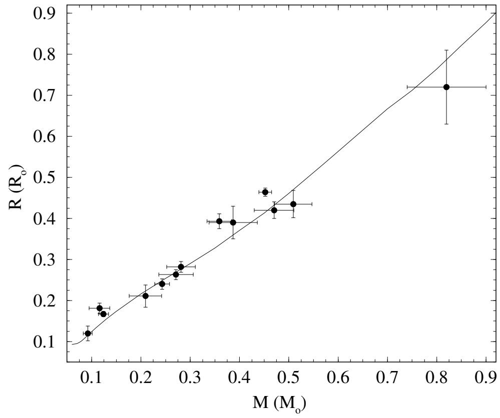

Fig. 2. Same as Fig. 1 (left) but for single-line and single-eclipse systems.

Finally, there is an additional source of fundamental properties of low-mass stars from direct interferometric measurements. This was the method applied in the recent study of Berger et al. (2006), where the authors report measurements for six M dwarfs with the CHARA array and suggested a correlation between radius differences and stellar metallicity.

In this context it is also worth reviewing the progress made in understanding the properties of the only known eclipsing binary with brown dwarf components. Following the discovery analysis of Stassun et al. (2006), the recent analysis of Stassun et al. (2007) has further refined the properties of the binary components and strengthened the case for a reversed temperature ratio, which is difficult to reconcile with model calculations.

3. Stellar activity hypothesis: a theoretical framework

As discussed by Ribas (2006) and Torres et al. (2006) there is a property that distinguishes low-mass stars in close binaries from those that are single objects, and this is the presence of tidal interactions that force the component stars to rotate in orbital synchrony. Because of strong observational biases, all low-mass eclipsing binaries found so far have periods well below 10 days, and, thus, rotation periods also below 10 days. Using the analysis of, e.g., Pizzolato et al. (2003) it is easy to realize that M stars with such short rotation periods will experience high levels of magnetic activity. This is also confirmed by the fact that most low-mass eclipsing binaries are strong X-ray sources and also they show intense emission in the Hα Balmer line.

From these observational facts it is sensible to consider a hypothesis by which the differences between model predictions and eclipsing binary observations arise from the high levels of magnetic activity of the component stars. Careful consideration of the effects of magnetic fields in low-mass stellar evolution models was carried out by Mullan & MacDonald (2001), using some prescriptions from Gough & Tayler (1966). The authors pointed out that the inclusion of magnetic fields potentially has a moderate impact on the overall stellar properties. More recently, Chabrier et al. (2007) have performed a more realistic treatment targeted specifically to resolving the current differences between observations and models. The authors have considered two scenarios. Firstly, a scenario that considers the effect of magnetic fields in causing inhibition of the convective energy transport. And secondly, a scenario similar to that proposed by López-Morales & Ribas (2005) and based on simple energy conservation arguments in a spot-covered surface.

The study of Chabrier et al. (2007) concludes that both mechanisms alter the properties of the star sufficiently to explain the observed radius and temperature discrepancies. In the case of the inhibition of convection, this was tested by setting the mixing-length parameter to lower values than that yielded by the standard solar model. The result on the structure of the star is that it shows a higher radius and slightly lower effective temperature. Tests show that good agreement with the observations is obtained for a mixing-length parameter of 0.5 pressure scale heights in the case of the more massive stars of the sample (i.e., $M > 0.6$ M$_\odot$). However, less massive stars are little affected by the lower mixing-length parameter and agreement with observations is only obtained when decreasing to (possibly unphysical) values of 0.1 pressure scale heights

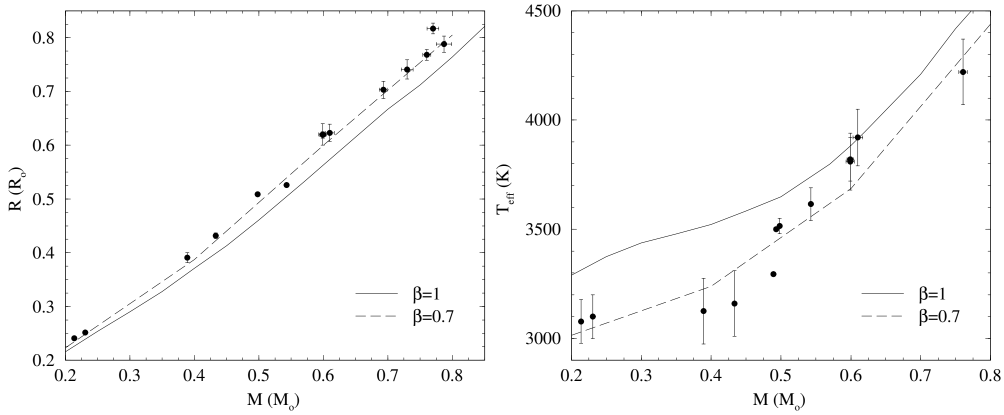

Fig. 3. Comparison of the best known eclipsing binary systems with models using β values of 0 and 0.3. Left: M–R plot. Right: M–$T_{\rm eff}$ plot.

or less. This is well illustrated in figure 1 of Chabrier et al. (2007).

In the case of the direct effect of starspot coverage, the analysis can be carried out by assuming a new luminosity L' expressed as

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

where R' is the modified radius, $T'_{\rm eff}$ is the modified effective temperature and β is the factor by which starspots block the outgoing luminosity because of their lower temperature. From the calculations of models with this modified boundary condition, Chabrier et al. (2007) found that the radii of low-mass stars in eclipsing binaries in the entire mass domain can be reproduced with a β parameter of about 0.3. Assuming a spot temperature contrast of about 15% (or 500 K), the results indicate that starspots cover approximately half of the stellar surface. In this scenario, the modified stellar effective temperatures are also found to agree with the observations as the total stellar luminosity is nearly invariant. In Fig. 3 we show a mass-radius plot and a radius-effective temperature plot that illustrate the good agreement between observations and models when considering the effects of starspots.

Thus, although conclusive evidence on which of the two scenarios (or perhaps a combination) is the most reliable to explain the observations is still lacking, the results of the analysis strongly suggest that stellar activity is a key element in understanding the properties of low-mass stars such as their radii and effective temperatures.

4. Stellar activity effects: test with observations

In this section we consider various observational evidence in the context of the stellar activity hypothesis. One of the straightforward questions to address is the universality of the hypothesis. In other words, if activity is thought to be responsible for the observed radius and effective temperature discrepancy in eclipsing binaries, do single active stars also show the same effect? Indeed, active stars have long been recognized to define a slightly offset sequence in the color-magnitude diagram (e.g., Stauffer & Hartmann 1986). The results from the eclipsing binaries and the theoretical studies discussed above allow for a fresh look at the problem. From the available evidence it can be assumed that the luminosities of low-mass stars are not significantly affected by stellar activity. The studies by Morales et al. (this volume) and Morales et al. (2007) show that a comparison of active and inactive stars of the same luminosity indeed reveals a systematic temperature offset. The effective temperature differential can be translated into a radius difference that is of the same order as that found in eclipsing binaries. This result generalizes the activity effects on stellar properties to any star, either single or binary. Full details on the analysis can be found in the references above.

The activity hypothesis was also investigated by López-Morales (2007), who collected values of rotational velocities and, eventually, X-ray luminosities of a sample of low-mass eclipsing binaries. Then, the radius discrepancies were searched for correlations with such X-ray luminosities, which are proxies to the overall stellar activity. The author identified significant correlations in the binary sample but not so in single stars with interferometric radius measurements. However, we must caution the reader that the dynamic range of the X-ray luminosities of single stars in López-Morales (2007) is very small and the overall scatter of the X-ray values will mask any correlation. Thus, the lack of inconclusive evidence in the single star analysis is not surprising.

There is yet another observational piece of evidence that adds to the discussion on the effects of activity on stellar properties. This is the detailed analysis of the only known eclipsing brown dwarf reported by Stassun et al. (2007). The surprising conclusion of the analysis was a statistically significant temperature reversal (i.e., the more massive brown dwarf is also the cooler of the pair), which is not compatible with the predictions of models. However, a recent study by Reiners et al. (2007) indeed shows that the more massive component is significantly more active than its less massive counterpart. Put in the context of our results above, it seems clear that higher activity would result in cooler temperature thus explaining the reversal found in the light curve analysis.

But there are also results that seem to be at odds with the hypothesis of stellar activity as being responsible for the $\sim$10% differential in stellar radii. The recent study by Torres (2007) used the particularities of planetary transits to determine the physical properties of the host star GJ 436. This star is relatively inactive, with a value $\log L_X/L_{\rm bol} = -5.1$ (compared with -3, which is typical of eclipsing binaries). Surprisingly, the author also found a 10% radius differential when compared with models, in agreement with the results from eclipsing binaries. More examples of such objects with transiting planets are desirable to draw any firm conclusions. However, in the meantime, we call attention to the fact that the analysis of GJ 436 is heavily based on an assumed stellar effective temperature, which is known to be poorly established in the low end of the main sequence, and thus potentially subject to large systematic errors.

5. Starspot coverage

One of the consequences of the starspot scenario discussed above is the need for a β value of 0.3 and thus about 50% surface coverage of spots cooler than the photosphere by 15% to explain the observed radius discrepancies. It is worth reviewing now if such high coverage is compatible with the observations. Interestingly, large spot coverages are intuitively associated with large photometric variations. This is indeed not the case. Photometric variations are only sensitive to the *contrast* between different areas on the surface of the star. Thus, a heavily spotted star with a homogeneous spot distribution would have its overall light level severely diminished but display no significant variations along the rotation phase.

We carried out various simulations to investigate if the eclipsing binary data in the form of light curves are compatible with the inferred surface spot coverage of about 50%. This was done by assuming different latitude distribution models and then evaluate the peak-to-peak magnitude variations. A detailed summary of our investigations will be provided elsewhere but here we point out that the simulated light variations out of the eclipses and the depth of the eclipses themselves are compatible with the observed light curves of several analyzed eclipsing binaries. An illustration of this can be seen in Fig. 4 for the case of the eclipsing binary YY Gem.

6. Other scenarios

Stellar activity is not the only scenario advocated to explain the reported differences between observed and model calculated stellar

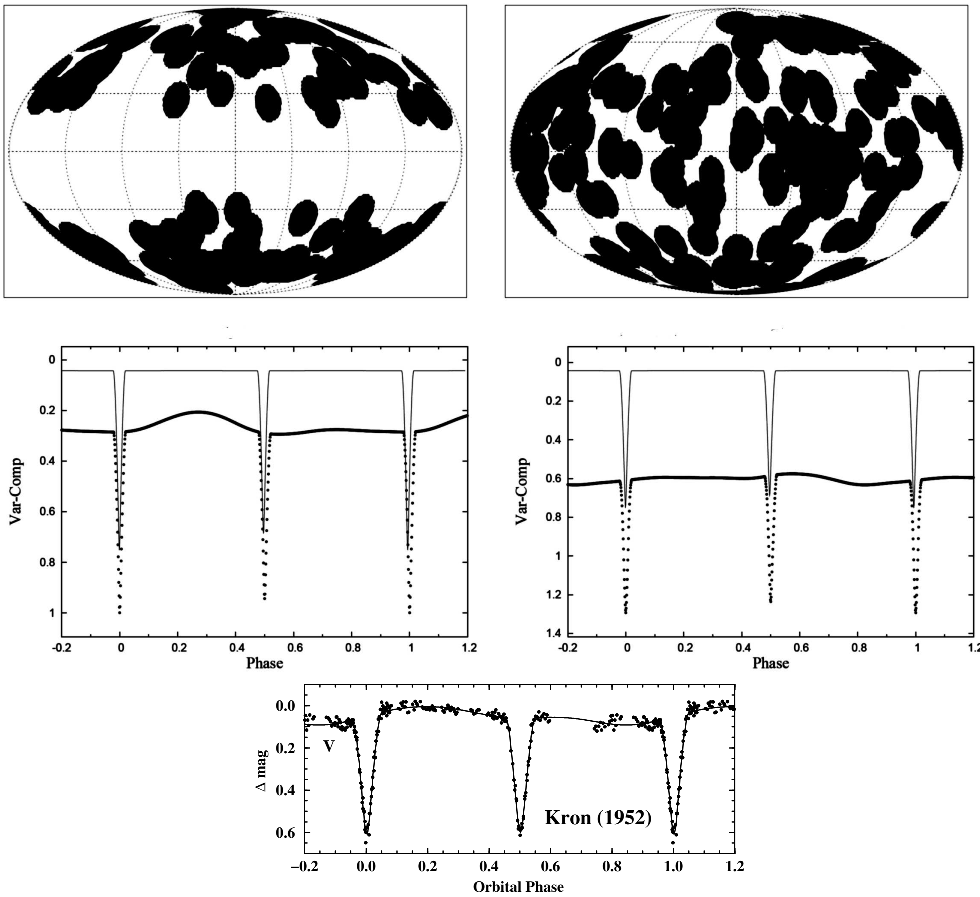

Fig. 4. Four top panels: Plots depicting two different latitude distributions of starspots covering 50% of the stellar surface. Note the different out-of-eclipse light drop and the resulting phase variations. Bottom panel: Observed light curve of the eclipsing system YY Gem in the *R* band.

radii. Berger et al. (2006) analyzed a sample of stars with interferometric radii and found quite a strong correlation between radius differences and stellar metallicity. From this evidence the authors conclude that the mismatch between observation and theory could be due to a missing source of opacity in the model calculations. However, a reanalysis of an extended interferometric sample by López-Morales (2007) failed to identify such strong correlation. In addition, the interferometric radii determined by Ségransan et al. (2003) with VLTI seem to agree well with model predictions. The possible relationship between radius differences and metallicity should be further investigated, both with additional data and with a statistically sound approach to evaluate the significance of the correlations found.

7. Conclusions

Without excluding at this point any other scenario, it seems clear from the tests discussed above that stellar activity plays a key role in defining the structure and radiative properties of low-mass stars. This could be very important in the context of young, and therefore active, low-mass stars, for example in clusters or star-forming regions. Failure to account for the effects of stellar activity can lead to strong potential biases in the determination of the ages of these objects and their ensembles. As discussed by Morales et al. (2007), a simple calculation using the temperature differentials found for single active stars indicates that ages of young clusters determined from (active) low-mass stars could be systematically underestimated by about 40%. Interestingly, this difference agrees well with the discrepancy between color-magnitude diagram ages and Li depletion boundary ages in young clusters (e.g., Barrado y Navascués et al. 2004).

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