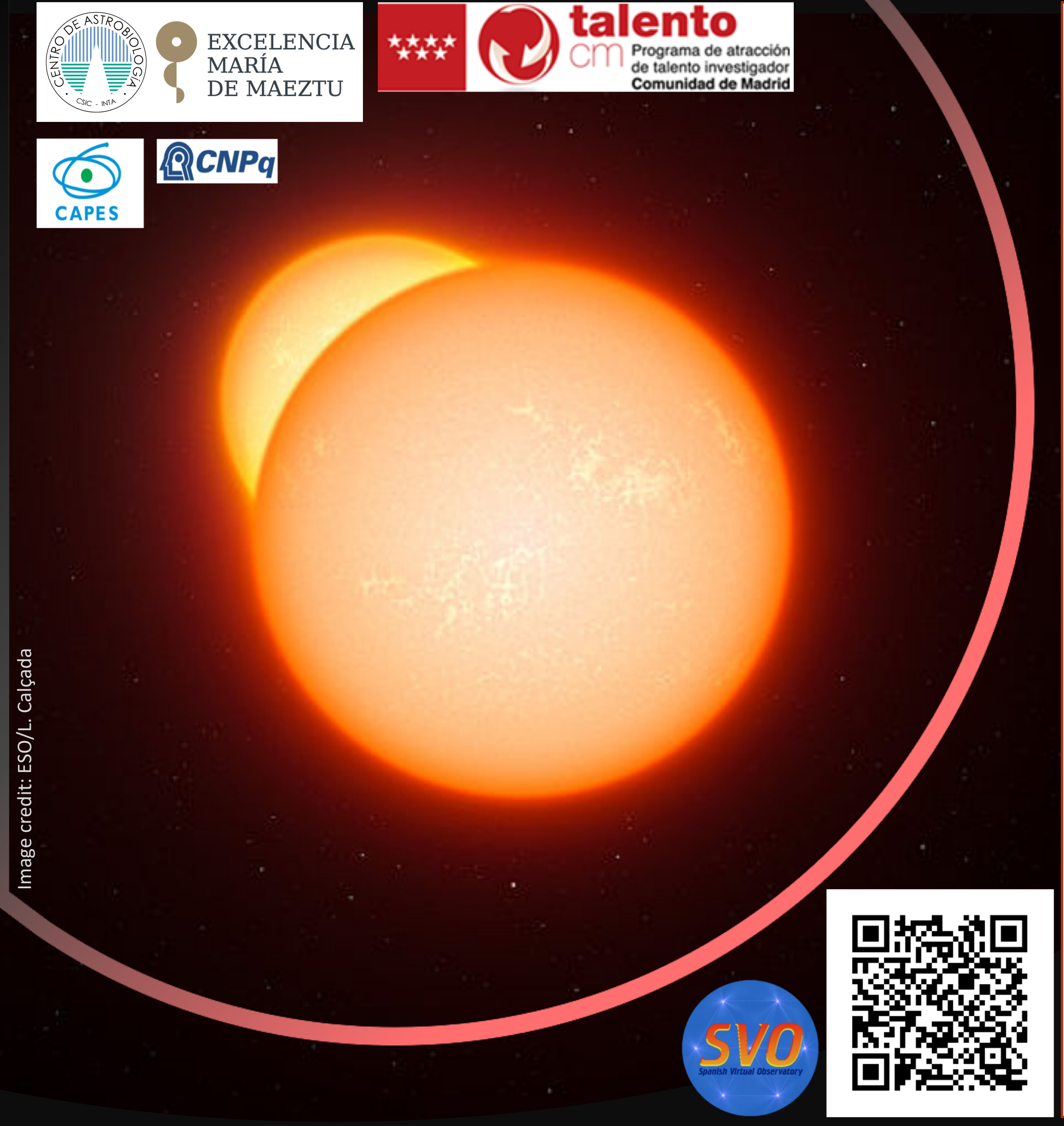


THE RADIUS ANOMALY IN SHORT-PERIOD ECLIPSING BINARIES: A LARGE-SAMPLE ANALYSIS

Patricia Cruz[1,2,3], Hernán E. Garrido[4], Marcos P. Diaz[3], and John F. Aguilar[5]

1: Centro de Astrobiología (CAB/INTA-CSIC), Spain; 2: Spanish Virtual Observatory (SVO), Spain; 3: Universidade de São Paulo (IAG/USP), Brazil; 4: Universidad de Córdoba, Colombia; 5: Universidad Militar Nueva Granada, Colombia

We have searched for detached low-mass eclipsing binaries (LMEBs) in the Catalina Sky Survey to determine their orbital and physical parameters and study the radius anomaly problem found in such systems. Here we present our results, where we have identified and photometrically characterised a sample of 230 detached close-orbiting LMEB systems, with main-sequence components only. These low-mass stars have effective temperatures of less than 5720 K and orbital periods shorter than 2 days. We adopted a purely photometric method to derive stellar parameters, such as the effective temperature, photometric mass, and fractional radius, by using the available light curves and photometric colours obtained from 2MASS and SDSS magnitudes. We modelled all light curves with the JKTEBOP code (suitable for detached systems), associated with an asexual genetic algorithm, to derive the best solution for orbital parameters and the radius of each component. The adopted method allowed an unprecedented analysis of such a homogeneous set of parameters for low-mass stars in short-period binary systems, despite large individual uncertainties. The distribution of the studied components in the mass-radius diagram not only confirms the radius inflation in low-mass main-sequence stars but also shows a relative increase of inflation towards lower masses. The distribution also suggests that the secondary components of these short-period systems are more inflated than the primary components, as they present larger radii than primaries of the same mass, when compared to stellar evolutionary models.

Motivation

Eclipsing binaries (EBs) give the most precise ways to derive stellar physical parameters (such as mass and radius) without the use of stellar models (Andersen 1991; Torres, Andersen & Giménez 2010).

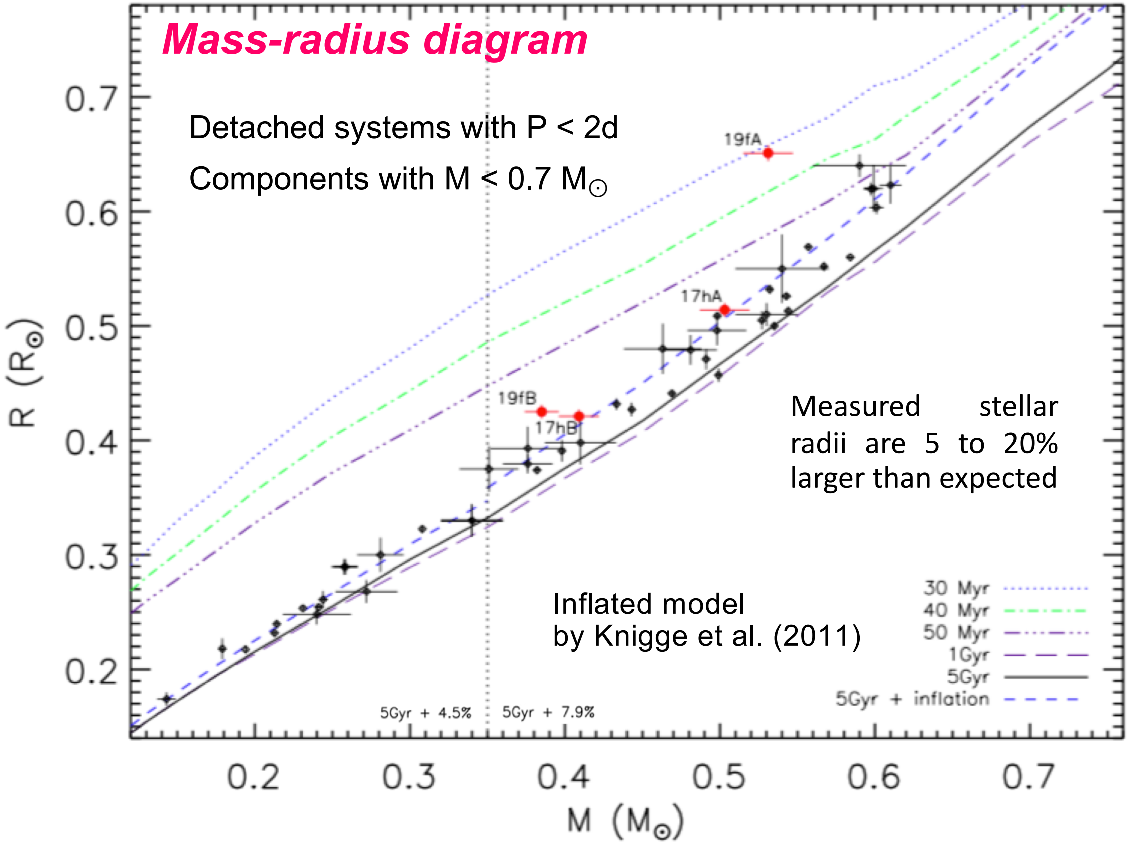
This work was focused on detached low-mass eclipsing binaries (LMEBs), which are non-interacting systems –as there is no mass transfer–, with components that are main-sequence stars (dwarfs) only, with masses of less than 70% of the mass of the Sun ($M < 0.7\ M_{\odot}$).

Why are these EBs interesting?

→ Only a small number of well-characterised LMEBs (those with masses and radii defined within an uncertainty of 5% or less) are found in the literature (Southworth et al. 2015).

→ Close-orbiting systems, with orbital periods of less than 2 days (P_{orb} < 2 days) present an intriguing trend: the measured stellar radii are usually 5 to 20% bigger than the expected value when compared to stellar models (López-Morales & Ribas 2005; Kraus et al. 2011; Cruz et al. 2018).

(Cruz et al. 2018, fig. 5, mod.)



Possible causes of the radius anomaly

Some possible causes were proposed over the last decade:

→ Missing physics in the equation of state (Irwin et al. 2011).

→ High metallicity (López-Morales 2007) would increase the stellar opacity and make the star to inflate to conserve radiative flux.

→ Isolated metal-rich M-dwarfs presented inflation, however no similar relation was found for components of EB systems.

→ High magnetic activity (Chabrier et al. 2007; Kraus et al. 2011) would suppress convection, making the star to inflate.

→ Active M-dwarfs in short-period LMEBs present inflation.

We then need a greater sample of model-independent LMEBs to investigate the causes of the radius anomaly.

Increasing the sample

To increase the number of well-characterised LMEBs, it is necessary a huge amount of telescope time dedicated to spectroscopically follow up the systems.
→ Different approach: a purely photometric method to fully characterise a selection of detached EB systems.

Getting temperatures and masses from broad-band photometry using clustering techniques

LMEBs selected from the Catalina Survey Periodic Variable Catalog (Drake et al. 2014) with $P_{orb} < 2$ days.
→ How to separate dwarf (V) from giant (III) systems?
The selected systems went under a supervised statistical analysis:

→ We constructed a **SDSS–2MASS ten-colour calibration grid** of synthetic composite colours.

→ We adopted the K-Nearest Neighbours classifiers method (Hartigan 1975) to assign the effective temperatures (Teff) for each component of the system.

→ The photometric masses were obtained from semi-empirical values of stellar colours and effective temperature sequence (Pecaut & Mamajek 2013).
(See Garrido, Cruz et al. 2019 for more details.)

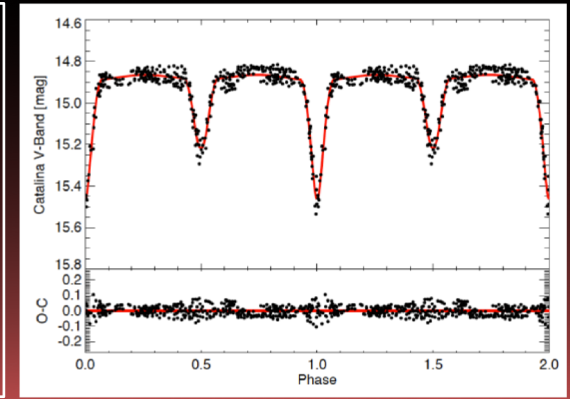
We identified as systems with only dwarf stars as components (V+V):

230 new detached LMEBs !!

Results from light curve modelling

Used JKTEBOP code (Southworth et al. 2004) plus an asexual genetic algorithm (Coughlin et al. 2011) for orbital and stellar parameters.

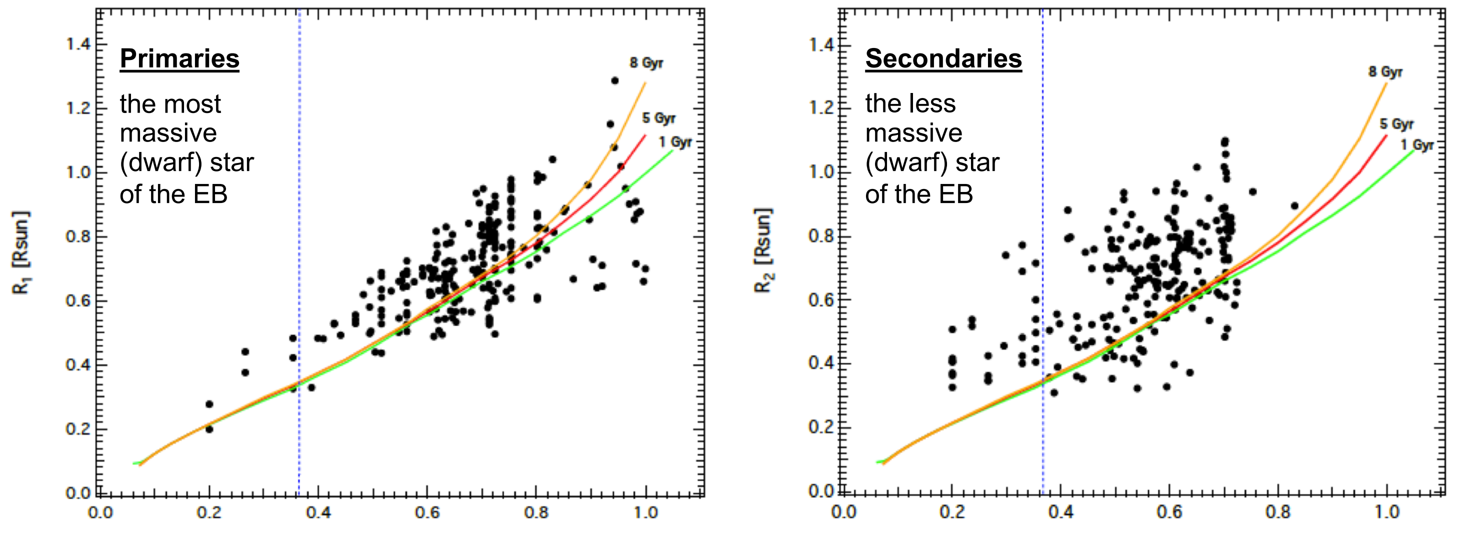
Phase-folded light curve of CSSJ034302.8+0.109354.



(Garrido, Cruz et al. 2019, fig. 3)

The mass-radius diagram: a large sample analysis

The figure below shows the mass-radius diagram for the 230 detached LMEB systems analysed by our method. Despite individual large uncertainties (as we do not have spectroscopic data) and concerning a general scenario, these results suggest that there is a global trend of inflation for low-mass stars.
In total, there are 460 individual stars and they were separated in two plots: primary and secondary components (panels below).
Intriguing and new: Secondaries seem more inflated than primary components!



(Garrido, Cruz et al. 2019, fig. 4)

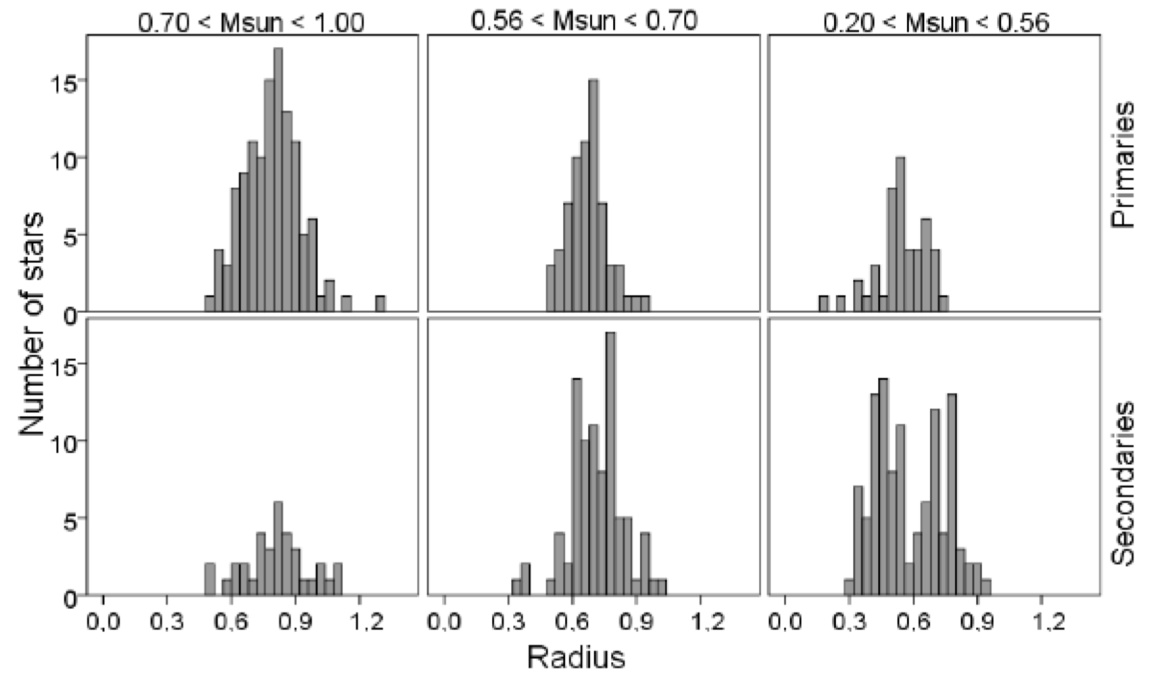
Are secondaries really more inflated than primaries? Why do they behave differently?

Are the secondaries more inflated? The Kolmogorov-Smirnov (KS) test

Our results suggest that secondary components are more inflated than primaries in short-period detached EB systems.

→ **61%** of the well-characterised LMEBs (systems with errors < 5%) in the literature also present more inflated secondary components!

To test if these two groups, primaries and secondaries, have a different behaviour –i.e., if they do not come from the same distribution–, we applied the KS test.



(Garrido, Cruz et al. 2019, fig.5 and table 2)

	Mass range ($M_\odot$)	Number of Primaries	Number of Secondaries	Number of stars per bin	Percentage (%)	Statistical significance
BIN 1	$0.70 < M < 1.00$	118	35	153	33.26	0.655
BIN 2	$0.56 < M < 0.70$	66	87	153	33.26	0.005
BIN 3	$0.20 < M < 0.56$	46	108	154	33.48	0.005

References: Andersen J., 1991, A&AR, 3, 91; Chabrier G. et al., 2007, A&A, 472, L17; Coughlin, J. et al., 2011, AJ, 141, 78; **Cruz, P**. et al., 2018, MNRAS, 476, 4, 5253; Drake A. J. et al., 2014, ApJS, 213, 9; Garrido, H., **Cruz, P.** et al., 2019, MNRAS, 482, 5379; Hartigan J. A., 1975, Clustering Algorithms. Wiley, New York; Irwin J. M. et al., 2011, ApJ, 742, 123; Knigge C. et al., 2011, ApJS, 194, 28; Kraus, A. et al., 2011, ApJ, 782, 48; López-Morales M., & Ribas I., 2005, ApJ, 631, 1120; López-Morales M., 2007, ApJ, 660, 732; Pecaut M. J., & Mamajek E. E., 2013, ApJS, 208, 9; Southworth, J. et al., 2004, MNRAS, 351, 1277; Southworth, J., 2015, 2015, ASPC, 496, 164S; Torres G. et al., 2010, A&A Rev., 18, 67.

All analysed stars (460 objects, 230 primaries + 230 secondaries) were divided into three bins of mass intervals. These ranges of mass were defined to have approximately a third of the whole sample in each bin (see table below).

→ The distributions change the pattern when we compare primaries (upper panels) to secondaries (lower panels), reaching larger radii for a same range of mass (see, for instance, panels on the far right), and presenting even a bimodal behaviour for the secondary components.

→ For the less massive objects in our sample ($M < 0.70\ M_\odot$; BINs 2 and 3), the significance of the KS test is only of 0.005, representing this different behaviour.

A very succinct discussion

The radius inflation problem found in low-mass stars, especially those that are components of close-orbiting EB systems, seems to be significant for more than half of the detached EBs in the literature. This work suggests that there is a global inflation trend in such low-mass objects, despite large individual uncertainties, which is even more significant for secondary components.

Our results also raised new questions:

– Why are the secondary components more inflated than primaries?

– Is the suggestion of a bimodal radii distribution a real trend?

– How does the secondary know it is the secondary to behave differently?

We also emphasise the importance of increasing the sample of known short-period detached LMEB systems, with homogeneously derived masses and radii, to investigate the causes of the radius anomaly. Such studies will help to improve theoretical stellar structure and evolutionary models, which will have an impact on several areas of stellar astrophysics where the mass-radius calibration plays an important role.