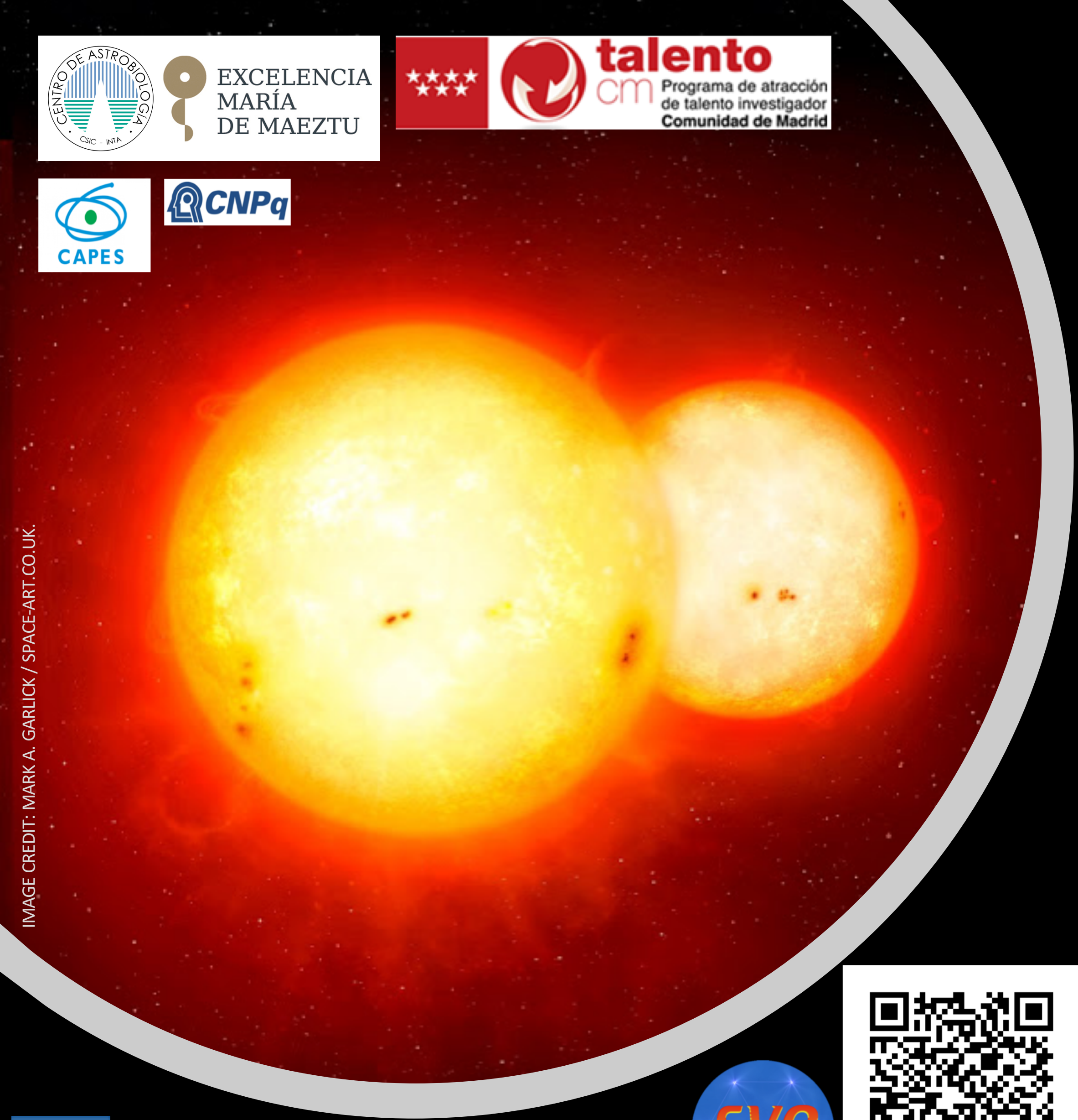


IMAGE CREDIT: MARK A. GARLICK / SPACE-ART.CO.UK.

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

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 low-mass eclipsing binaries (EBs) in the Catalina Sky Survey, with the objective of determining their orbital and physical parameters and studying the radius anomaly problem present in such systems. Here we present our results, where we have identified and photometrically characterized a sample of 230 detached close-orbiting EB 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 effective temperature, photometric mass, and fractional radius, by using the available light curves and the photometric colors obtained from 2MASS and SDSS magnitudes. We modeled all light curves with the JKTEBOP code, suitable for detached systems, associated with an asexual genetic algorithm to derive the best solution for the orbital parameters and the radius of each component. The analysis of such homogeneous set of parameters allowed an unprecedented analysis of the mass-radius diagram of 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 of low-mass main-sequence stars but also shows a relative increase of inflation for lower masses. The distribution also suggests that the secondary components of such 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.

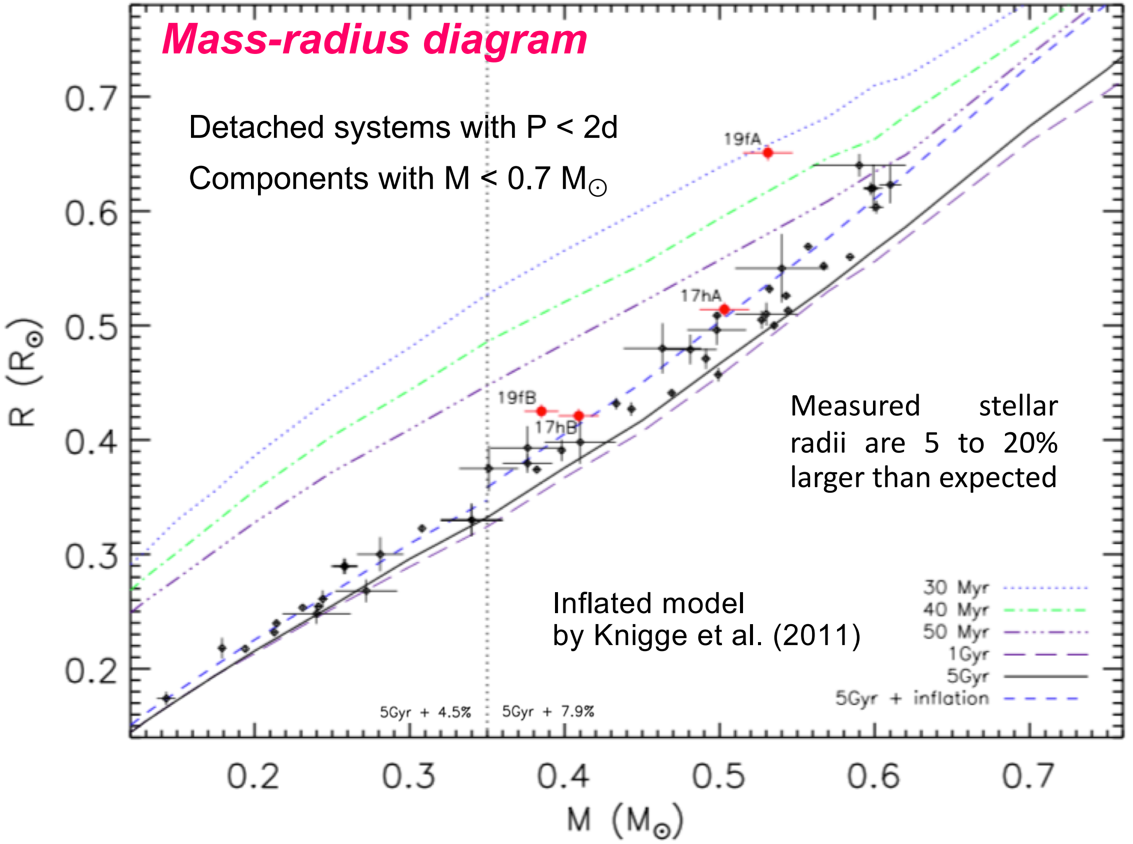
Motivation

– Eclipsing binaries (EBs), particularly detached spectroscopic double-lined systems, give the most precise ways to derive stellar physical parameters without the use of stellar models (Andersen 1991; Torres, Andersen & Giménez 2010).

Why focus on low-mass ($M < 0.7\ M_{\odot}$) EBs?

– Only a small number of well-characterized LMEBs are found in the literature (Southworth et al. 2015).
– Close-orbiting systems (P_{orb} < 2-3 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.)



Mass-radius diagram

Detached systems with $P < 2d$
Components with $M < 0.7\ M_{\odot}$

Measured stellar radii are 5 to 20% larger than expected

Inflated model
by Knigge et al. (2011)

Possible causes of the radius anomaly

Several possible causes were proposed over the last decade:

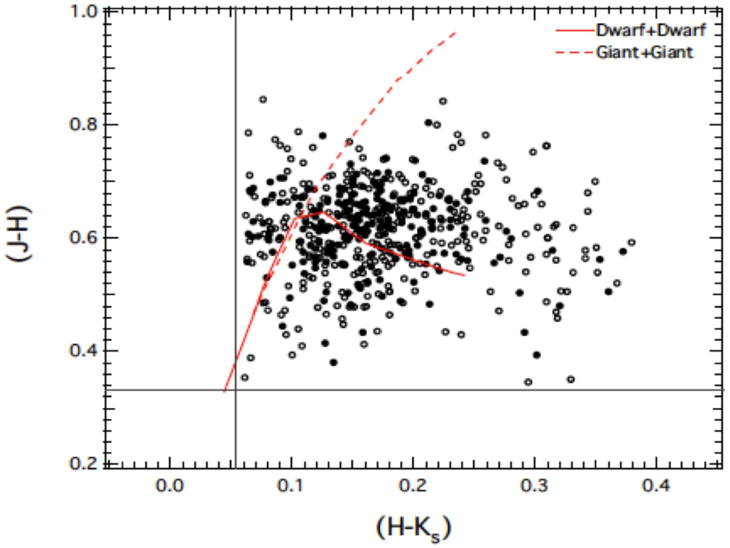
– Missing physics in the equation of state (Irwin et al. 2011).
– Metallicity (Lopez-Morales 2007) → Isolated metal-rich M-dwarfs presented inflation, however no similar relation was found for components of EB systems.
– Magnetic activity (Chabrier et al. 2007; Kraus et al. 2011) → Active M-dwarfs in short-period LMEBs present inflation.

We then need a greater sample of model-independent well-characterized LMEBs.

Methodology

Searched for detached EBs (DEBs) in the Catalina Sky Survey (Drake et al. 2009).
→ CSDR1, CSDR2 (Drake et al. 2012, 2014)

Adopted criteria:
– Detached systems with periods shorter than 2 days in the "Catalina Survey Periodic Variable Catalog" (Drake et al. 2014).
– Systems with components later than G3 dwarfs only ($T_{eff} < 5720$ K; $M < 1\,M_{\odot}$), initially identified by using a $(H - K)-(J - H)$ diagram.



(Garrido, Cruz et al. 2019, fig. 1)

How to separate dwarf from giant systems?

Getting temperatures and masses from broadband photometry: using clustering techniques

The binary systems went under a supervised statistical analysis which uses clustering techniques to search for similarities between observed data and models, based on a multi-color dataset.

→ We constructed a SDSS–2MASS **ten-colors calibration grid** of synthetic composite colors (see Garrido, Cruz et al. 2019 for more details).

→ We used 990 models: synthetic binaries created by combining models with 30 different temperatures for a main sequence star and 14 different temperatures for giants (based on the 1 and 3 Gyr models from Bressan et al. 2012)
→ 3 possible combinations: III+III; III+V; and V+V systems.

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

The photometric masses were then obtained from the semi-empirical values of stellar colors and effective temperature sequence by Pecaut & Mamajek (2013).

→ From this method we have identified as V+V systems:

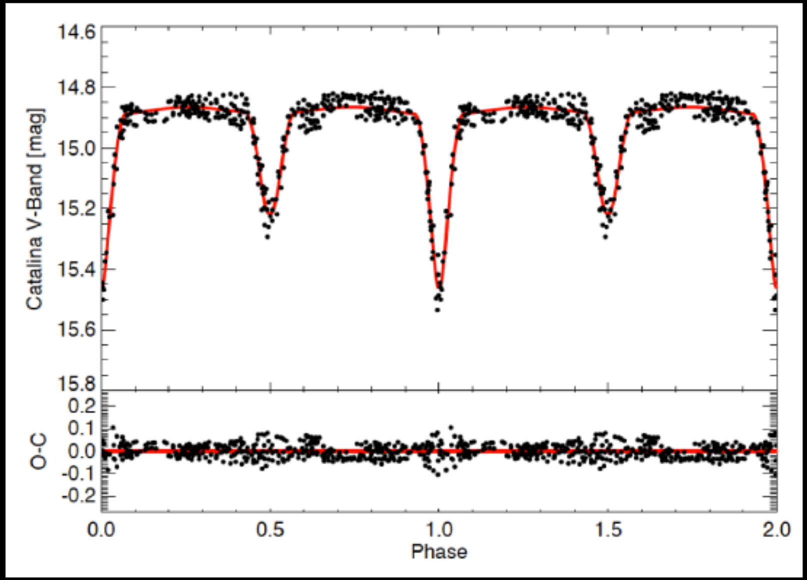
230 DEBs with LMMS (Low-Mass Main Sequence) stars!

We, then, solved the systems with photometric data only.

Results from light curve modeling

We used the JKTEBOP code (Southworth et al. 2004) modified with the Asexual Genetic Algorithm (Coughlin et al. 2011) for the light curve modeling of our 230 detached EB systems.

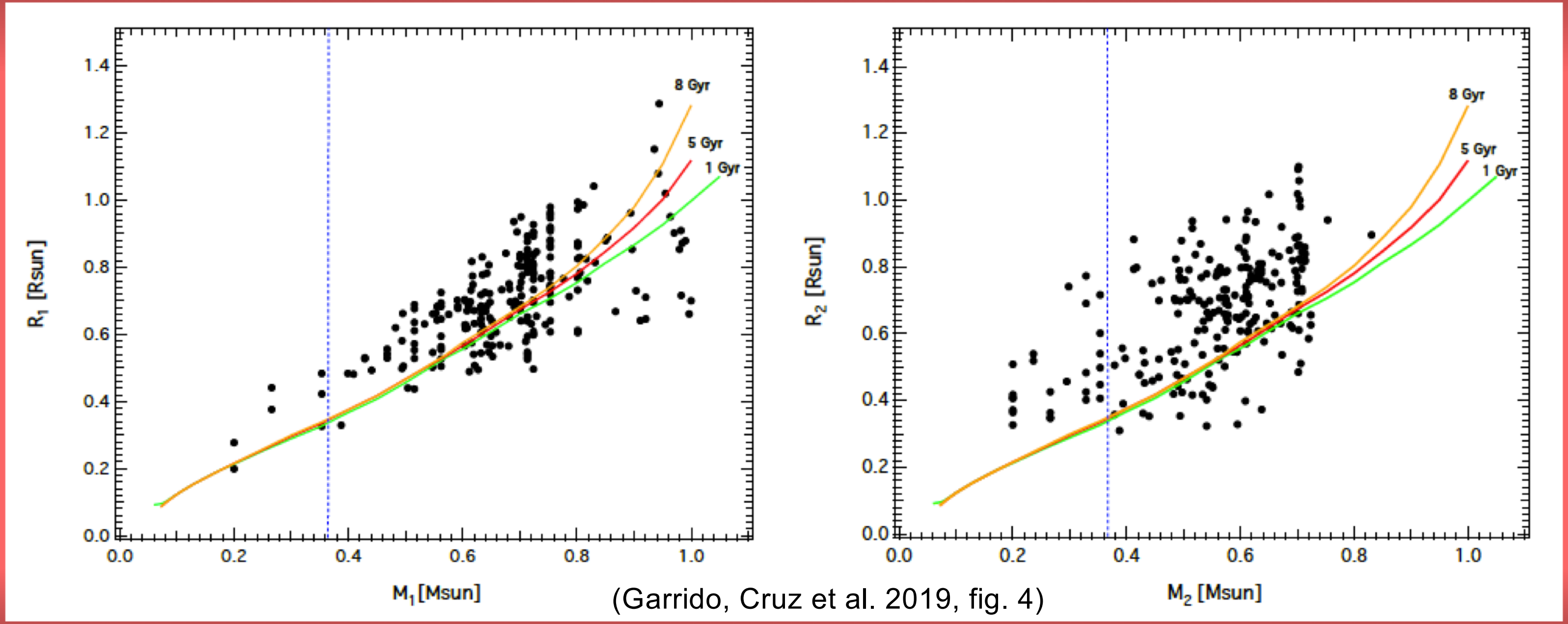
As a result, we obtained:
→ Orbital parameters (binary separation, orbital inclination angle, refined period and reference time of primary minimum) + fractional radii.



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

The mass-radius diagram: from a large sample analysis

The figure below shows the mass-radius diagram for the 230 DEB systems analyzed by our method. Despite individual large uncertainties, 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 here in two plots: for primary (left panel) and secondary (right panel) components. Secondaries seem more inflated than primary components.



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

Are secondaries really more inflated than primaries or is this some kind of visual effect?

Are the secondaries more inflated? The Kolmogorov-Smirnov test

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

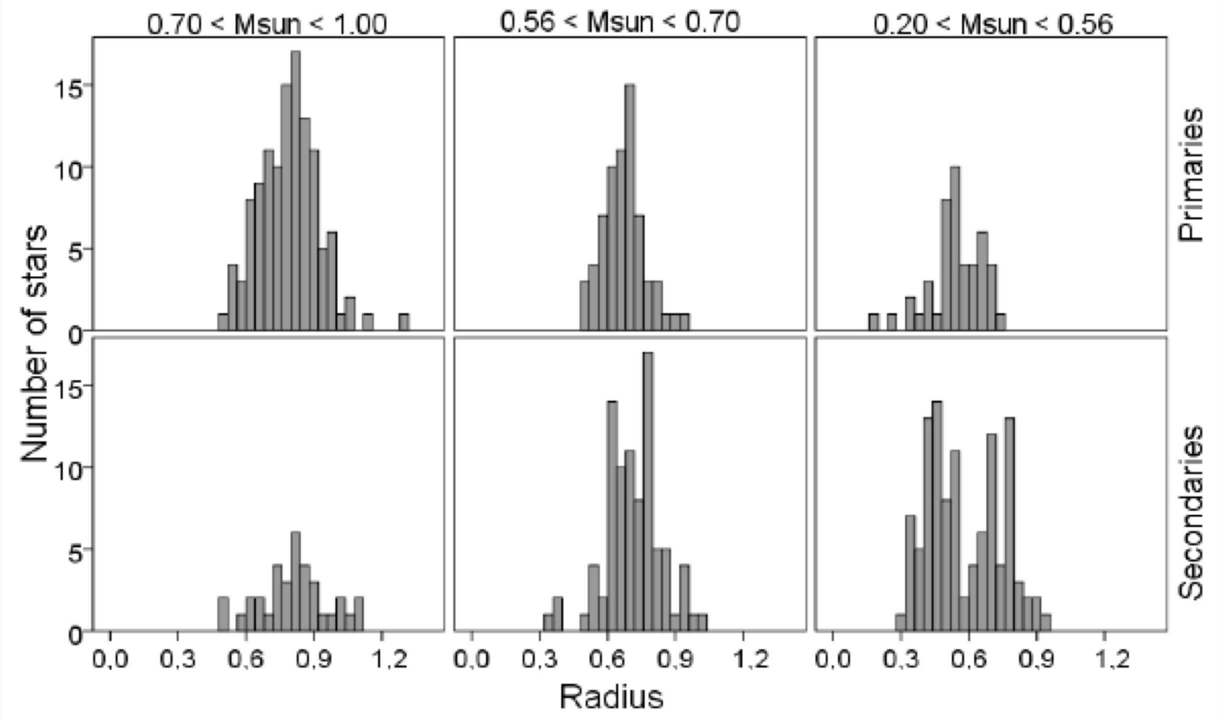
→ From the literature: **61%** of the well-characterized (with errors < 5%) low-mass EBs also present more inflated secondary components.

To test if these two groups, primaries and secondaries, have different behavior, i. e. if they come from the same distribution, we applied the Kolmogorov-Smirnov (KS) test.

All analyzed 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).

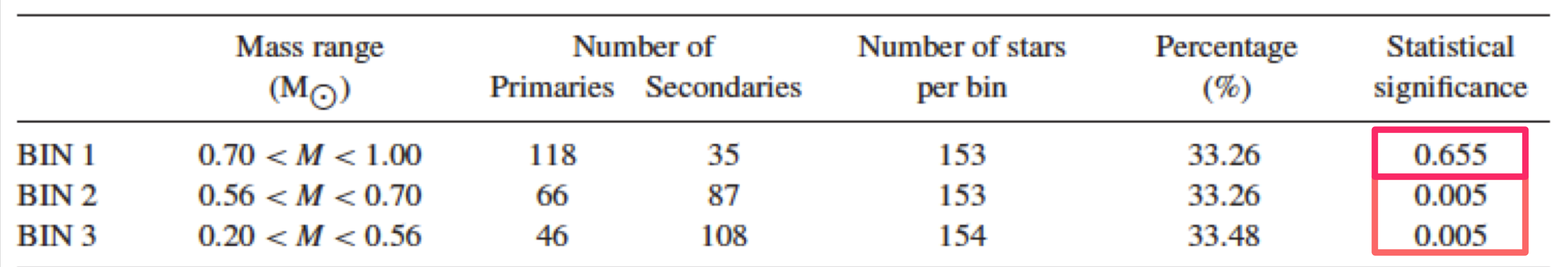
The distributions changes the pattern when we compare primaries (upper panels) to secondaries (lower panels), reaching larger radii for a same range of mass (see, for instance, panels on the far right) and presenting even a bimodal behavior for the secondary components.

(Garrido, Cruz et al. 2019, fig. 5)



→ 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.

(Garrido, Cruz et al. 2019, 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

The analysis of large samples is important and can reveal additional global trends. Indeed, our results support the radius anomaly previously found in low-mass stars though model-independent characterization (photometry + spectroscopy), however, they raise new questions:

– Why the secondary components are 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 continue to investigate this subject by analyzing large samples…

Very succinct conclusion

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 well-characterized detached EBs in the literature. This work suggests that there in a global inflation trend in such low mass objects, despite large individual uncertainties, which is even more significant for secondary components. We emphasize the importance of increasing the sample of known short-period detached EB 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.

The persistence of the radius anomaly in low-mass stars:
Using VO tools to search for short-period eclipsing binaries in large photometric surveys

We recently started to expand the presented method as a first intent to answer the questions asked above. A very brief summary of the mentioned project, which will be developed in the next four years under an “Atracción de Talento” grant, is:

→ Apply the purely-photometric method from Garrido, Cruz et al. (2019) to available photometric surveys (Kepler and TESS);
→ Identify and photometrically characterize low-mass components of short-period EBs;
→ Spectroscopically follow up the most interesting candidates distributed in the fully-convective and the partially-radiative regimes.

References: Andersen J., 1991, A&AR, 3, 91; Bressan, A. et al., 2012, MNRAS, 427, 127; Chabrier G., Gallardo J., Baraffe I., 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., 2009, ApJ, 696, 870; Drake A. J. et al., 2012, American Astronomical Society Meeting, 219, 428.20; 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., Baraffe I., Patterson J., 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., Andersen J., Giménez A., 2010, A&A Rev., 18, 67.