TESS photometry of *crème de la crème* of Eclipsing Binaries

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Since 2011 we have been conducting an extensive spectroscopic survey of detached eclipsing binaries (DEBs), and obtaining precise radial velocity (RV) data for hundreds of them. The main goal was to identify and properly characterise new cases of poorly-studied or astrophysically interesting stars (e.g. low mass dwarfs, PMS, giants, pulsators, multiples, etc.). For most of them, we also gathered 2-minute cadence time series photometry from the TESS satellite through Guest Investigator programmes. Thanks to the superb data sets we are able to derive the values of fundamental stellar parameters (e.g. absolute masses, radii, temperatures) with a very high relative precision of 0.2-2%. To date we have identified for example DEBs ∼80 with low-mass stars, 15 with (sub)giants, ∼10 with pulsators of various kinds, ∼90 multiples, or 5 with pre-main sequence components, as well as a number of systems with other interesting properties.

1 Introduction

Detached eclipsing binaries (DEBs), especially those that are also double-lined spectroscopic (SB2) pairs, are one of the most useful objects in astrophysics. Their importance can not be overestimated, as they are used, for example to: test models of stellar structure and evolution, derive observational calibrations, test stellar formation theories, provide high-precision distances, characterise extrasolar planet hosts, etc. Many crucial stellar parameters, like mass, radius, effective temperature, age, or metallicity, can be derived simultaneously and accurately only from DEBs. Therefore, it is an ongoing effort of many researchers, to provide as many cases of thoroughly studied systems as possible, with a comprehensive set of information. So far, fewer than 300 DEBs have the desired level of uncertainty in masses or radii (<2%), and a large fraction still does not have reliable information about the age and metallicity (Southworth, 2015). Furthermore, many interesting classes of stars, and many areas of the H-R diagram, are underrepresented among the best-measured stars. For this reason, a large observational survey, dedicated for searching and characterising interesting stars in DEBs, has been started.

2 The CRÉME project

2.1 Spectroscopic data

The *Comprehensive Research with Échelles on the Most interesting Eclipsing binaries* (CRÉME) is an observational project of high-resolution spectroscopic observa-

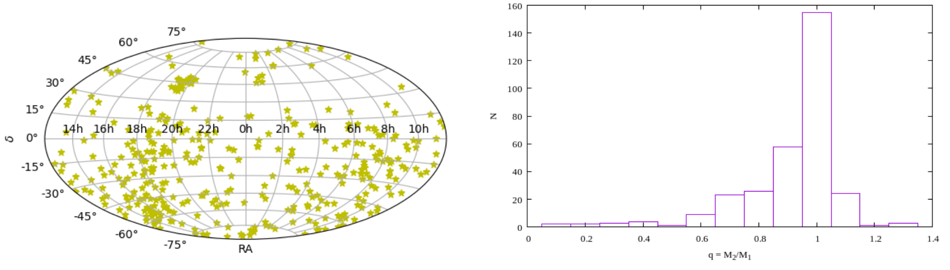

Fig. 1: *Left*: The all-sky projection of CRÉME targets. The southern hemisphere is more populated, because of the major source of targets — the ASAS catalogue (declination limit at $\delta < +28$ deg). The concentration of targets around $\alpha \sim 19$ h, $\delta \sim +45$ deg represents the *Kepler* field. *Right*: Histogram of mass ratios (secondary over primary) of 315 double-lined DEBs from the CRÉME project. Due to the traditional convention of labelling primary and secondary components with respect to the eclipse depth, the primary is not always the more massive one.

Tab. 1: Statistics of telescope time granted for the CRÉME project.

Telesc./Spectr.	Time	Telesc./Spectr.	Time	Telesc./Spectr.	Time
OAO-188cm/HIDES	87.5 n	TNG/HARPS-N	16 n	Subaru/IRCS	4.5 n
SMARTS 1.5m/CHIRON	673 h	AAT/UCLES[a]	11 n	Magellan-Clay/PSF	4 n
Euler/CORALIE	40 n	ESO 3.6m/HARPS	10 n	NOT/FIES	4 n
MPG-2.2m/FEROS	30 n	Subaru/HDS	4.5 n	OHP 1.9m/SOPHIE	3 n

Note: With additional data from Radcliffe/GIRAFFE[a], OUC-50cm/PUCHEROS, Keck I/HIRES, TNG/SARG, Hamilton/HamSpec; and archives: ESO, SOPHIE, ELODIE, KOA, APOGEE.
[a] Observations taken before 2011.

tions, intended to derive precise radial velocity (RV) measurements and atmospheric parameters. The main goals of the project are:

1. Identification of new examples of rare, poorly studied, or otherwise interesting DEBs.

2. Precise characterisation of the studied systems i.e. determination of masses, radii, temperatures, distances, metallicities, and ages of stars.

The project goals were defined and the observations started in 2011, and initially targeted a sample of southern hemisphere DEBs, identified by the All-Sky Automated Survey (ASAS; Pojmański, 2002). It was a successor of a previous search for low-mass stars (2005-2010), and a small-scale survey of F- and G-type DEBs (2008-2009) made with iodine cell spectrographs (Hełminiak et al., 2009). In 2013 CRÉME has been extended to the northern hemisphere, with a significant portion of targets coming from the main field of the *Kepler* mission. The intensive spectroscopic campaign lasted till 2017, but since then additional data have been taken for selected objects, if needed.

At the moment (December 2021) the CRÉME target sample consists of 377 DEBs (Figure 1). A total of ∼6900 spectra has been gathered with 18 spectrographs attached to 16 telescopes (from 0.5 to 10-m apertures) or were found in public archives. The total telescope time granted to the project exceeded 300 nights (Table 1).

The project intended to observe relatively bright ($V < 12.5$ mag) and "red" ($V - K > 1.1$ mag) systems, so a sufficient precision of RVs would be possible to obtain. However, several early-type objects with large $E(B-V)$ were included and later kept in the sample. Out of the 377 systems observed within CRÉME, 32 were marked as not qualified for further studies, 22 were found to be single-lined (SB1), 3 early-type systems pose difficulties in RV determination and require an individual approach, and 5 systems do not have enough sufficient RV measurements ($N < 4$). Therefore, we currently have 315 systems with a sufficient number of good-quality data to estimate orbital parameters and masses of the components[1].

Masses alone, or even the orbital solutions, can already point towards some of the interesting properties, such as: location on the cool (<0.9 $M_\odot$) or hot (>3 $M_\odot$) parts of the main sequence; location inside the instability strips (γ Dor, δ Sct), or multiplicity (especially in hierarchical triple SB+3, or quadruple SB+SB configurations). In CRÉME we have so far 76 individual low-mass and 19 high-mass stars, 14 confirmed and 8 candidates for pulsating stars in DEBs, or 80 multiples of various architectures, including tight triples (outer period $P_3 < 1000$ d; TTS) and SB+SB quadruples.

2.2 TESS Guest Investigator programmes

To obtain the required precision in parameters, especially radii, one needs photometric measurements taken with high enough precision, sufficient cadence, and phase coverage. It quickly became clear that the publicly available data from such projects as ASAS or SuperWASP are not enough for the purposes of CRÉME, so additional dedicated observations had to be taken. This turned out to be very time-consuming and ineffective, especially when comes to the orbital phase coverage. Only the objects from the *Kepler/K2* fields had sufficient data available. Therefore, after the launch of the Transiting Exoplanet Survey Satellite (TESS; Ricker et al., 2015), we started applying for 2-minute-cadence photometry of the CRÉME targets through the TESS Guest Investigator (GI) programs. These programs allow to dedicate part of the mission's resources to scientific research outside of the main mission goals. We have been successful during all four cycles of the mission.

At the moment of writing this article, the TESS satellite is observing in Sector 47 during its fourth cycle of operations. A total of 252 CRÉME targets have their 2-minute cadence photometry, including: 150 in one sector, 59 in two sectors, 24 in three, 6 in four, 11 in 5 to 12 sectors, and 2 in at least 13 sectors. Additionally, 10 more targets were in the satellite's field of view, thus the 30-minute cadence data are available, and another 29 systems are expected to be observed by the end of Cycle 4.

3 CRÉME+TESS results

In Figure 2 we present masses and radii of components of 282 binaries collected in the DEBCat catalogue, together with 50 systems with published[2] orbital and physical parameters based on CRÉME data. One can note on the mass-radius panel that the CRÉME targets appear in regions poorly populated by the DEBCat objects, which shows that the goals of the project are possible to achieve. Notably,

[1]Technically only the lower mass limits $M\sin^3(i)$, but in DEBs $\sin^3(i) \simeq 1$, therefore they are good proxies of true stellar masses.

[2]Including preliminary solutions presented on conferences, and results based on pre-2011 observations.

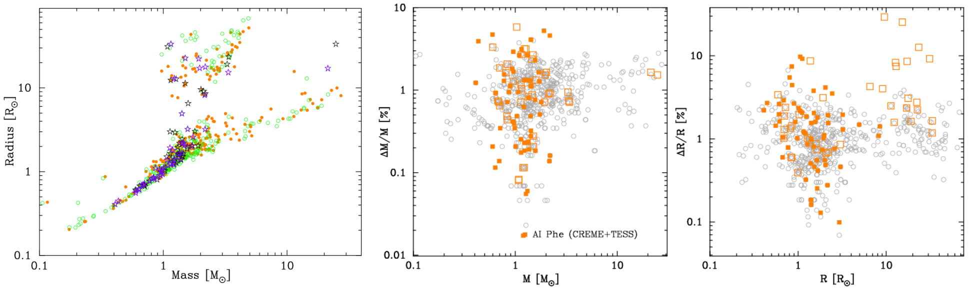

Fig. 2: *Left*: Masses and radii of binary components from the DEBCat catalogue (orange for primaries, green for secondaries) and CRÉME DEBs published so far (black for primaries, purple for secondaries). *Center* and *Right*: Same objects, but on parameter-error planes for mass and radius. CRÉME targets are marked with orange. Results that utilise satellite photometry (*Kepler/K2* and TESS) are marked with solid symbols, while open symbols are for ground-based-only data.

about 20 CRÉME targets are now listed in DEBCat, thus some points may overlap. Out of these, solutions for five systems also utilise TESS photometry from our GI programmes. These are: AI Phe (Maxted et al., 2020), V1200 Cen (Marcadon et al., 2020), HS Hya (Lee et al., 2020), ASAS J051753-5406.0, and ASAS J090232-5653.4 (Ratajczak et al., 2021). In general, we can note that satellite-borne photometry allows for smaller errors in radii.

3.1 AI Phoenicis

Analysis of the TESS light curve from Sector 2 was performed simultaneously and independently by a number of researchers, using different codes and assumptions (Maxted et al., 2020). Their individual results were later compared in order to verify their robustness, assess the code-independent systematics, and evaluate realistic parameter errors. It was found that TESS data allow for uncertainty in fractional radii at the level of ∼0.2%.

CRÉME observations include data taken already in 2008 (Hełminiak et al., 2009), and the monitoring still continues. AI Phe was quickly found to be a triple, after a long-term modulation in the centre-of-mass velocity was noted (Fig. 2, left in Hełminiak et al., 2015). Till date, we have taken 168 high-resolution spectra. The orbital solution based on those results, still with incomplete coverage of the outer orbit and without non-Keplerian effects, results in $K_1 = 51.162(16)$ and $K_2 = 49.101(18)$ km/s, and 0.07-0.08% fractional error in $M \sin^3(i)$ (1.1924(9) and 1.2424(9) $M_\odot$). The combined CRÉME+TESS solution (for $i = 88.359(6)$ deg) is marked in Fig. 2.

3.2 V1200 Centauri

This bright triple was identified as a PMS candidate with a low-mass secondary by Coronado et al. (2015), but the uncertainty in the secondary's radius was too large for secure conclusions ($R_2 = 1.10(22)$ $R_\odot$). With TESS data, and additional CRÉME spectra (Marcadon et al., 2020), we manage to confirm the PMS nature of

Tab. 2: Radii of a sample of low-mass stars in DEBs with solutions available in the literature, compared to new analyses, based on TESS photometry. All values are in $R_\odot$.

	Literature		New results	
Object	R_1	R_2	R_1	R_2
ASAS J011328...	0.594±0.020	0.445±0.024	0.607±0.012	0.445±0.012
AE Fornacis	0.670±0.030	0.630±0.030	0.674±0.007	0.617±0.010
ASAS J093814...	0.772±0.012	0.769±0.013	0.774±0.006	0.771±0.006

the system ($M_2 = 0.863(8)$ $M_\odot$, $R_2 = 1.154(14)$ $R_\odot$), and improve the R_2 error by a factor of 15. We also concluded that the outer body, on a short period ($P_3 \simeq 180$ d), is most likely a binary itself, due to its large minimum mass (0.87 $M_\odot$) and no traces of the third set of lines in the spectra. Additionally, it was impossible to fit a single isochrone to this system, thus we concluded that the primary appears to be ~10 Myr older than the secondary. This may be a hint that the outer body had a significant influence on the inner binary during its formation.

3.3 *Low-mass DEBs*

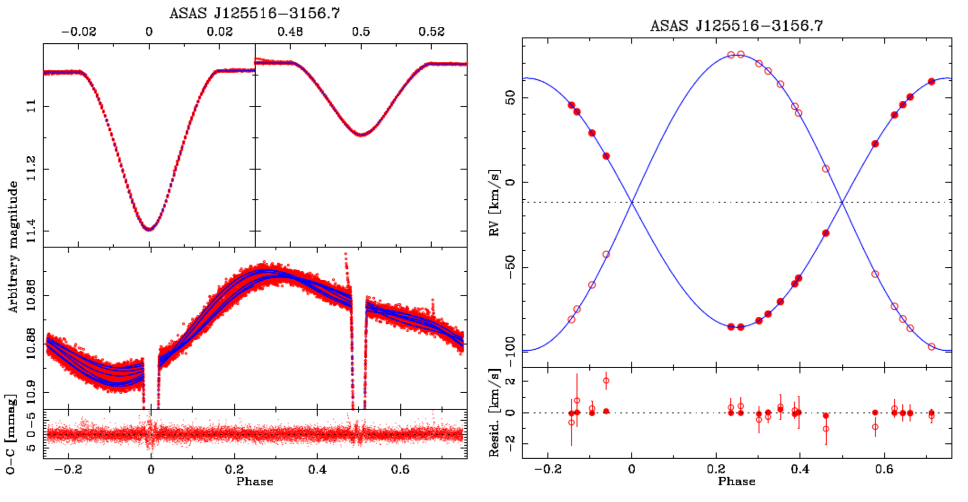

Fig. 3: Light curve (*left*) and orbital (*right*) solutions for ASAS J125516-3156.7.

The advantage of TESS data over the ground-based photometric observations (even very precise ones) can be seen for example in the results for active, low-mass DEBs. We have analysed light curves of several such objects, including AE For (Różyczka et al., 2013), ASAS J011328-3821.1 (Hełminiak et al., 2012), or ASAS J093814-0104.4 (Hełminiak et al., 2011). In Table 2 we compare the radii from literature with new results based on TESS light curves. Despite the substantial activity and the unstable character of the light curves, the improvement is clear.

Apart from these systems, we have made models for some objects, not yet described in peer-reviewed publications. An example is ASAS J125516-3156.7 ($P =$

3.057 d), for which we made 17 visits within the CRÉME project (Figure 3). The combination of CRÉME+TESS data resulted in the following masses and radii (all in solar units): $M_1 = 0.7104(25)$, $R_1 = 0.669(4)$, $M_2 = 0.5989(13)$, $R_2 = 0.557(8)$. A publication that will describe at least 14 DEBs with both components masses below 0.9 $M_\odot$, including the aforementioned four, is now in preparation.

4 Conclusions

The combination of CRÉME spectroscopy and TESS photometry allows us to obtain high-precision stellar and atmospheric parameters for a large number of DEBs. In our sample of targets, we have 315 binaries, of which 277 have satellite-borne photometry. Assuming the distribution of mass and radius uncertainties will be similar as in Fig. 2, we estimate that this sample will allow us to obtain 2% level of M and R errors for about 240 systems, 0.5% for about 50, and below 0.1% for about 10. In masses alone, we should reach 0.1% precision for about 30 cases. Publications that focus on low-mass stars, pulsators in DEBs, and TTS are now in preparation.

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References

Coronado, J., et al., *MNRAS* **448**, 2, 1937 (2015)

Hełminiak, K. G., Konacki, M., Ratajczak, M., Muterspaugh, M. W., *MNRAS* **400**, 2, 969 (2009)

Hełminiak, K. G., et al., *A&A* **527**, A14 (2011)

Hełminiak, K. G., et al., *MNRAS* **425**, 2, 1245 (2012)

Hełminiak, K. G., et al., in S. M. Rucinski, G. Torres, M. Zejda (eds.) Living Together: Planets, Host Stars and Binaries, *ASP Conference Series*, volume 496, 76 (2015)

Lee, J. W., Hong, K., Kristiansen, M. H., *PASJ* **72**, 3, 37 (2020)

Marcadon, F., et al., *MNRAS* **499**, 2, 3019 (2020)

Maxted, P. F. L., et al., *MNRAS* **498**, 1, 332 (2020)

Pojmański, G., *Acta Astron.* **52**, 397 (2002)

Ratajczak, M., et al., *MNRAS* **500**, 4, 4972 (2021)

Ricker, G. R., et al., *Journal of Astronomical Telescopes, Instruments, and Systems* **1**, 014003 (2015)

Różyczka, M., et al., *MNRAS* **429**, 2, 1840 (2013)

Southworth, J., in S. M. Rucinski, G. Torres, M. Zejda (eds.) Living Together: Planets, Host Stars and Binaries, *ASP Conference Series*, volume 496, 321 (2015)