Stars and their variability observed from space
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RR LYRAE AND CEPHEID VARIABLES WITH *TESS*

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Abstract. The space-based photometry revolution that started with *MOST, CoRoT, Kepler* and *BRITE* is being continued with *TESS*. The scope of *TESS* is different from that of its predecessors, in that it monitors the whole sky on shorter time-scales instead of observing selected fields for longer. This approach provides us with new possibilities – and challenges – to investigate variable stars of any type. This paper focussed on RR Lyrae and Cepheid stars, and summarizes our preliminary conclusions as to how these stars can benefit from *TESS* data. The first results from *TESS* observations of RR Lyrae and Cepheid stars will not be discussed here, as they will be presented in detail in the near future, in collaboration with *TESS* Asteroseismic Science Consortium Working Group 6.

Keywords: Stars: variables: RR Lyrae, Stars: variables: Cepheids, techniques: photometric

1 Introduction

RR Lyrae and Cepheid stars are key objects in many fields of astronomy: stellar structure and evolution, distance determinations, population studies and pulsation theory and, as such, are well-studied variables. A simplified view of these stars is that they exhibit radial pulsations (usually in the fundamental mode, less frequently in the first overtone mode, or simultaneously in both), with only rare cases where higher overtone pulsation occurs. However, the contemporary picture is much more complex, and many additional phenomena exist in these stars that can often only be recovered from high-precision light-curves. Many of these more recent discoveries still await theoretical explanation.

2 Hot topics

This section is a collection of the most relevant topics that challenge our theories, and where *TESS* observations will provide us with important new knowledge.

2.1 Pulsation properties

The oldest and most famous problem concerning RR Lyrae stars was described long before the start of space-based observations. Many examples of amplitude and phase modulations have been reported and studied in detail, and in a statistical sense since the discovery paper of Blažko (1907). For the state of the art concerning the Blazhko effect we refer to the latest studies by Smolec (2016); Prudil & Skarka (2017); Jurcsik et al. (2018); Netzel et al. (2018). Continuous space-based measurements were needed to reveal an additional phenomenon, *viz.* period doubling, which has been observed only in Blazhko RR Lyrae stars so far (Szabó et al. 2010). This effect is the sign of nonlinear dynamics in the pulsation caused by a resonance with a high-order mode (Kolláth et al. 2011; Smolec & Moskalik 2012). The occurrence rate, duration and stability of period doubling, and its relation to the modulation or pulsation properties, are as of now mostly unknown. Period doubling is manifested as an amplitude alternation in the light-curve and as a series of small frequency peaks in the Fourier transform, midway between the harmonics of the pulsation frequency. But other small-amplitude frequency components may also appear in the Fourier spectra, be they fundamental (RRab), overtone (RRc) or double-mode (RRd) RR Lyrae stars, modulated or non-modulated (Benkő et al. 2014, 2019; Netzel & Smolec 2019). The positions of these peaks in RRc stars are near where high-order nonradial modes should be excited (Dziembowski 2016). The first and second radial overtone frequencies can be identified tentatively among the low-amplitude peaks in RRab stars, but the origin of many other peaks remains unknown (Molnár et al. 2017b).

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Cepheid stars also exhibit all the phenomena mentioned above, but with some differences in strength and occurrence within the types and subtypes. The modulation in classical Cepheids is not as prominent as in RR Lyrae stars (Derekas et al. 2017), though many examples of weak modulation were found in the Magellanic Clouds durinig a systematic search through OGLE observations (Smolec 2017). The only exception, where modulation reaches a high amplitude, is V473 Lyr (Molnár et al. 2017a). This unique star exhibits period doubling, too. Period doubling and modulation were also reported in each subtype of the Type II Cepheid class (Smolec et al. 2018). Quasi-periodic modulation often co-exists with further irregular variations in the pulsation period and/or phase in these stars. Period doubling seems to be common among the long-period Type II Cepheids, so much so that amplitude alternations are considered to be the main characteristic of the RV Tauri type. Period doubling appears to be common as well in intermediate-period, or W Vir stars, for pulsation periods greater than 15 days; those stars may belong to an older population than the rest (Soszyński et al. 2019b). In contrast, only a handful of period-doubled stars were found among the short-period BL Her-type pulsators. The distribution of non-radial modes in overtone Cepheids shows strong similarities to that of the RRc stars when visualized in the Petersen diagram, where clear sequences, potentially connected to different spherical degrees, can be distinguished (Smolec & Śniegowska 2016). On the other hand, additional modes in the fundamental-mode classical Cepheids seem to show no pattern at all (Süveges & Anderson 2018), in contrast to the clear regions of peaks in RRab stars (Molnár et al. 2017b). Instabilities and cycle-to-cycle variation in the pulsation is common in Type II Cepheids: the longer the period the stronger the effect. However, this phenomenon is very weak in the classical Cepheids. Before the era of space-based photometry, those stars were considered to be clockwork pulsators, but the photometric accuracy of *Kepler* and *MOST* showed that that is not the case (Derekas et al. 2012; Evans et al. 2015).

The most pressing questions concerning pulsation—nonlinear effects (modulation, period doubling), low-amplitude additional modes (overtones and non-radial modes), and other instabilities (period jitter, cycle-to-cycle changes)—all require high-precision, continuous, and long observations.

2.2 Proper classification

Better knowledge of the pulsation properties helps us distinguish between various subtypes and filter out the non-pulsating impostors. Classification algorithms applied to sparsely sampled photometric surveys are often confused by other high-amplitude variables (Drake et al. 2017; Udalski et al. 2018; Rimoldini et al. 2019). The confusion usually occurs between variable types that have a common period range and similar light-curve shapes, such as W UMa eclipsing binaries and RRc stars, or rotational variables and Cepheid stars. The fraction of non-Cepheid stars among Cepheid candidates can be exceptionally large. Similarly, short-period Cepheids can easily be confused with RR Lyrae stars. One-day aliases in ground-based measurements may cause mis-identifications between BL Her stars and RR Lyrae stars.

Identifying anomalous Cepheids in the Galactic field is also challenging, since their period range overlaps both those of the Cepheids and the RR Lyrae stars (Jurkovic 2018). However, they differ in luminosity, and have their own period–luminosity relations for the fundamental and first overtone stars, respectively, which could be utilized to find them. Unfortunately, the *Gaia* DR2 parallaxes are not precise enough to classify individual pulsating variables yet (Ripepi et al. 2019), but we hope that the situation will change with the next data release. For the moment, light-curve morphology seems to be a more reliable classifier. The Fourier parameters (R_{21}, R_{31}, ϕ_{21} and ϕ_{31}), determined by (Simon & Lee 1981), provide quantitative measures of the light-curve shape, and by plotting them as a function of the period we can identify groups of the different types of variable. That method has also been used in the OGLE classification, and turned out to be successful in identifying anomalous Cepheids (Soszyński et al. 2017).

Single-mode overtone pulsation in Type II Cepheids is very rare; the first two such objects have been found only recently (Soszyński et al. 2019a) through careful analysis of the OGLE collection. This research was inspired by the recent discovery of the first double-mode BL Her stars (Udalski et al. 2018). The results show nicely that a statistically large sample of high-quality light-curves can still be used to recover new subtypes among radial pulsators.

2.3 Physical properties

Asteroseismology became an important tool for determining fundamental stellar parameters in the era of space-based photometry, and it is now common practice to estimate mass, radius and age from solar-like oscillations of main-sequence and evolved stars (Chaplin et al. 2014; Yu et al. 2018). A similar breakthrough has not yet been achieved for radial pulsators, but our increasing knowledge of pulsation properties, along with state-of-the-art pulsation and evolution models, has the potential to extraact physical properties from light-curves in the future. Promising steps have recently been taken to constrain the model parameters mass, metallicity and temperature from multi-colour light-curve data (Bhardwaj et al. 2017). It has also been shown that, besides the pulsation period, the light-curve structure can play a statistically significant role in determining global stellar parameters (Bellinger et al., in prep.). Further effort is required to map these connections among observations and model light-curves. An important and essential part of that work is to recover the differences and similarities in the light-curve properties between populations and subtypes.

Until then we can rely on binarity, which offers another great opportunity to determine stellar parameters accurately. Seeking eclipsing binary candidates among Cepheids and RR Lyrae stars is therefore an important task. A few systems containing Cepheid members have already been analyzed in detail in the Magellanic Clouds (Pilecki et al. 2018) and within the Galaxy (Gallenne et al. 2019). Several new binary candidates have been proposed recently from proper-motion anomalies detected in *Gaia* DR2 (Kervella et al. 2019). The latter study also contains binary RR Lyrae candidates. The expected binary fraction among RR Lyraes stars is significantly smaller (∼7%) than in Cepheids (∼80%), but because they are much more numerous we have good chances of finding multiple examples. The (O–C) technique is an effective tool for searching for companions; however, the light-travel time effect causes cyclical variations in the (O–C) diagram similar to Blazhko modulation; it therefore gives reliable results only for non-modulated stars (Prudil et al. 2019).

3 Observing with TESS

The main goal of the *TESS* mission is to discover the nearest exoplanets that orbit relatively close to their host stars (Ricker et al. 2015), but as with *CoRoT, Kepler* and *K2* it is expected to be a significant contributor to the fields of asteroseismology and stellar variability, including heat-driven pulsating stars. *TESS* was designed to be an all-sky survey, and in its 2-year prime mission it is already covering most of the sky, dividing the field of view into 26 partially overlapping sectors that rotate around the ecliptic poles. The telescope has a 21"/px angular resolution. A milli-magnitude level of accuracy can be achieved for stars brighter than 12th magnitude in the *TESS* passband (T_{mag}); the photometric precision drops to about 1% per long-cadence data point for a 16-T_{mag} star. The next Section discusses how Cepheid and RR Lyrae investigations are constrained by the properties of *TESS*, and what data products are available.

3.1 Benefits

The undoubted strength of the *TESS* ission is the size of the area observed. Such a large part of the sky has never been observed continuously from space. Each of the sectors is monitored for 27 days, a length that is adequate for recognizing RR Lyrae and even short-period Cepheid pulsations. Only a handful of Cepheid stars have been observed continuously from space so far; thus, a big step will be taken with *TESS* inasmuch as it is able to observe all Cepheids in the Galaxy and the bright ones in the Magellanic System as well. With its faint limit we are only able to sample the RR Lyrae population in the solar neighbourhood. The benefits of high-precision, continuous space-based photometric data are clear: from precise light curves we can determine accurate Fourier parameters and (O–C) diagrams, and recover low-amplitude modes and other weak changes in pulsations. *TESS* data will enable us to study many of the hot topics mentioned in Section 2 in a huge sample of classical variables. A significant fraction of Cepheid and RR Lyrae targets are in the overlapping areas of the sectors or (as for the Large Magellanic Cloud) in the continuous viewing zone. The latter area is being observed for nearly a year, providing an opportunity to study the longer-period Cepheids and the Blazhko effect in RR Lyrae stars.

3.2 Limitations

As for all space missions, *TESS* also has some inherent limitations. Perhaps the most constraining feature is the low angular resolution. The image of a stellar object has a diameter of 2–3 pixels in *TESS* images. Given the 21-″ pixel size, many blends are observed. The contamination is especially critical in dense stellar fields such as the Magellanic Clouds, the Galactic bulge and even the Galactic plane; those areas are where most of the Cepheids can be found (Fig. 1).

Contamination can cause several problems in an analysis, even if the brightness variation of the blended star is negligible. The extra flux may change the shape of the ligh-curve, and thence the Fourier parameters. Blends may therefore affect classification and other studies that use those parameters, such as the estimation of photometric metallicity. When the contaminating star is itself a variable, extra peaks may appear in the

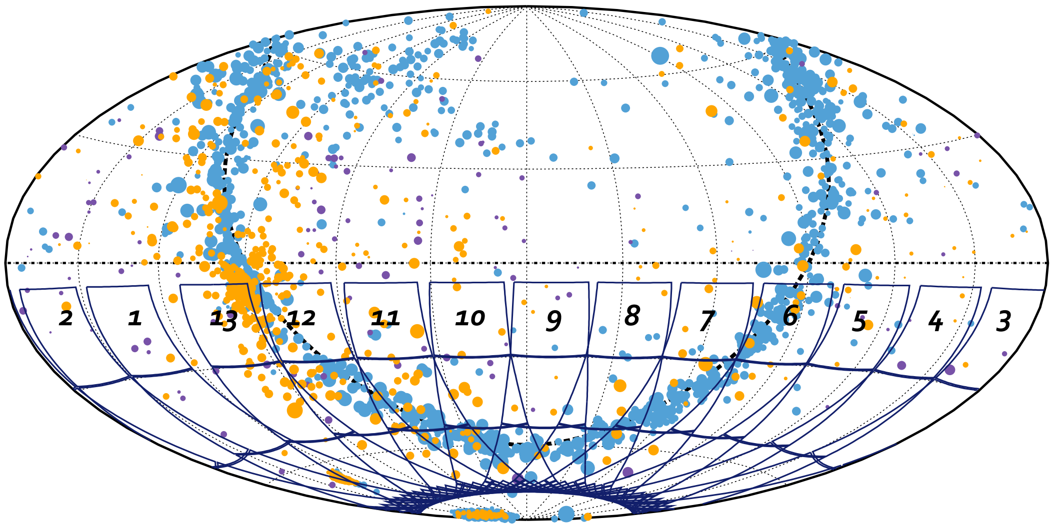

Fig. 1. Distribution of Cepheid stars in the ecliptic coordinate system: classical Cepheids (blue), Type II Cepheids (orange), anomalous Cepheids (purple). The southern *TESS* sectors are also marked.

composite Fourier transform, and which can easily be misidentified as additional pulsation modes. Moreover, in dense stellar fields it is possible that more than one Cepheid star can fall within the same aperture. Blends are able to cause fake cycle-to-cycle variations and features that resemble amplitude modulation.

The targets observed in multiple sectors can have extended light-curves after stitching the data sets together. The technique of stitching is not straightforward. A similar problem was experienced with the original *Kepler* mission as a consequence of rotation of the telescope, when data of different campaigns were joined: the average flux and the pulsation amplitudes were different owing to differences in pixel sensitivity (Benkő et al. 2014). No perfect solution has been developed for this problem. In the case of *TESS*, this issue is even more pressing because the contaminating stars in the large pixels can differ significantly in each sector, and may prevent us from studying cycle-to-cycle variations and other low-amplitude features in crowded areas.

The 27-day-long observation is fine for unmodulated RR Lyrae stars, but nearly half of the fundamental-mode stars are Blazhko stars, and the period of the Blazhko modulation is rarely shorter than 27 days. We may therefore not be able to study the Blazhko effect in detail, or even recognize a long-period modulation extending to hundreds or thousands of days in a single-sector light-curve. Those can only be achieved in the continuous viewing zone. We face a similar situation for the Cepheid stars, too. In contrast to RR Lyrae stars that have pulsation periods shorter than a day, the range of Cepheid periods extends up to a hundred days, so we expect more success when observing the shorter-period stars. However, owing to the Cepheid period–luminosity relation, shorter-period objects are fainter, and that is critical in the Magellanic Clouds and the Bulge, where visibility is seriously constrained by this confusion. Fortunately, a period range where Cepheids can still be fruitfully studied can nevertheless be found.

Finally, we ask how the faintness of RR Lyraes affects investigations. The brightness distribution of Galactic RR Lyrae stars that were recently identified in *Gaia* DR2 by Clementini et al. (2019) showed that the majority of RR Lyrae stars are fainter than $T_{mag} = 16$ (Fig 2). This raises the question of how deep we can go with *TESS* photometry, and what we can achieve with noisy data. Preliminary tests suggest that the RR Lyrae variability is still recognizable at 17.5 T_{mag}, suggesting that these data are still useful in classification and validation of RR Lyrae catalogues based on sparsely-sampled data, but modulation or additional modes cannot be recovered any more.

3.3 Data availability

The *TESS* mission* provides target pixel files and light-curves produced by the Science Processing Operations Center (SPOC) at NASA Ames Research Center, for the pre-selected 2-minute cadence targets, which are

*https://heasarc.gsfc.nasa.gov/docs/tess/

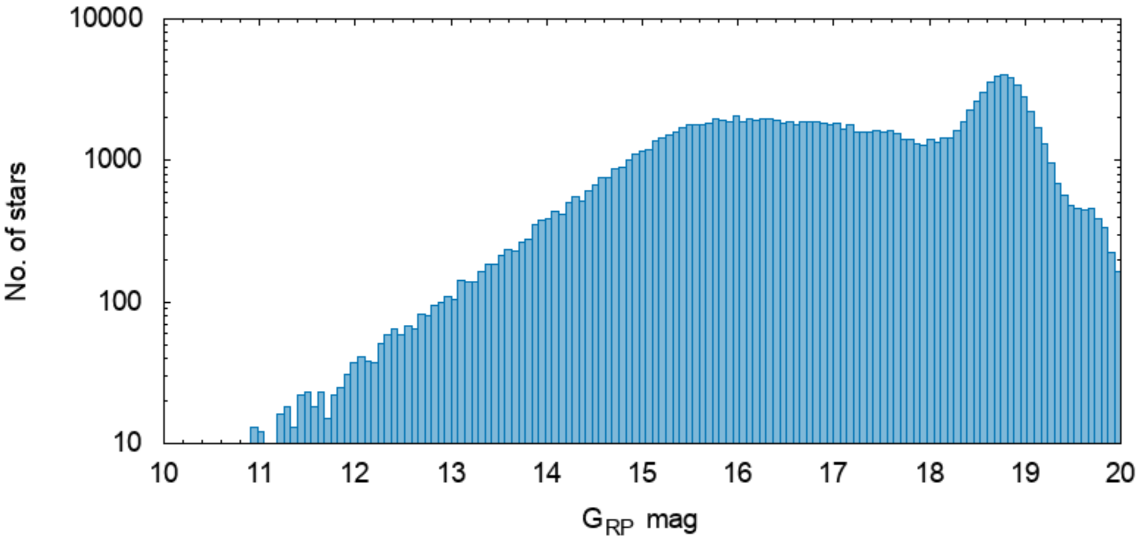

Fig. 2. Brightness distribution of RR Lyrae stars in *Gaia* DR2 in the G_{RP} passband, which is similar to that of *TESS*.

available at the MAST Archive †. The working groups (WGs) of the *TESS* Asteroseismic Science Consortium (TASC) proposed almost 38 thousand asteroseismic targets for the 2-minute cadence in the prime mission. WG6 focuses on RR Lyrae and Cepheid stars, and proposed 89 important or peculiar targets for the short-cadence mode. All other RR Lyrae and Cepheid targets are in the full-frame images (FFIs) that are taken with a 30-minute cadence. The mission does not provide light-curves for the ∼150 million stars (< 16 T_{mag}) in the FFIs; that task has to be organised by the scientific community, by using separate pipelines or open-source codes developed for *TESS* photometry – for example, `eleanor` (Feinstein et al. 2019) and `lightkurve` (Lightkurve Collaboration et al. 2018). Data releases are in progress by the *TESS* Data for Asteroseismology (TDA) Coordinated Activity of TASC at the *TESS* Asteroseismic Science Operations Center (TASOC) and by other groups too (Oelkers & Stassun 2019). To get a first look at *TESS* RR Lyrae and Cepheid stars we have prepared difference-imaging aperture photometry using the FITSH package (Pál 2012) developed at Konkoly Observatory. The pipeline corrects many of the instrumental and intrinsic differences between the target frames and the reference frame (differential velocity aberration, spacecraft jitter, background and stray-light variations, strap reflection, momentum wheel dumps), and provides suitably high-quality data to search for low-amplitude phenomena.

4 Conclusions

The *TESS* mission will be a determining factor in space-based photometry in the following years. It is hard to estimate how many new important results will come out from *TESS* observations, but we can definitely predict that, after *Kepler* revolutionized RR Lyrae and Cepheid investigations through its unprecedented photometric precision, *TESS* will revolutionize the field again because of the high number of stars observed. However, we have to be very careful with the analysis of low-amplitude signals because of the strong contamination from nearby objects.

This work has been supported by Lendület LP2014-17 and LP2018-7/2018 grants and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. This work presents results from the ESA mission *Gaia*. *Gaia* data are being processed by the Gaia Data Processing and Analysis Consortium (DPAC). Funding for DPAC is provided by national institutions. I thank László Molnár and Róbert Szabó for proofreading this manuscript.

† https://archive.stsci.edu/tess/

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