The TESS RR Lyrae and Cepheid Survey

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Abstract

TESS provides a unique possibility to observe bright RR Lyrae stars and Cepheids over the entire sky continuously, hence provide information on recently discovered dynamical phenomena, like Blazhko modulation, period doubling, shock-wave propagation, and additional modes. Ground-based follow-up observations ensure that multicolor and spectroscopic information will be utilized to unravel the atmospheric processes at play. RR Lyrae, the prototype which is recovering from a complete disappearance of its Blazhko effect will be a flagship target in addressing the long-standing enigma, the Blazhko modulation.

Cadence

We propose to observe the listed targets with ***2-minute*** cadence to (1) **resolve fast and sharp features in the light curves of RR Lyrae stars and Cepheids**, such as the bumps caused by shock waves reaching the stellar surface, (2) **obtain well-sampled extrema of the pulsation cycles** to investigate non-linear phenomena, cycle-to-cycle variations and temporal behavior of period doubling, (3) investigate the **amplitude distribution of the harmonics** in RR Lyrae light curves to provide more constraints on the dynamics of their atmosphere, (4) search for optical counterparts of observed X-rays flashes in Cepheids.

Length of time series

Most of our targets will be observable in one or two TESS pointings: for these stars, we propose 2-min cadence observations for at least one pointing. Two targets will provide a unique possibility to monitor the temporal behavior of their ongoing dynamical phenomena: XZ Dra and ST Pic are located in the northern and southern Continuous Viewing Zone, respectively. XZ Cyg will be observable in 3-4, Polaris for 2-3 27-d cycles within overlapping regions, respectively. We propose to follow them as long as possible as high-priority targets.

In general, during a 27-day run 40-60 RR Lyrae pulsational cycles will be observed (80-100 cycles for RRc variables). This is enough to cover short modulation periods, and to detect signs of longer modulation periods. A 27-day observational window will be barely enough to see changes in the bump caused by shock waves, but longer coverage (as in the case of XZ Dra and XZ Cyg) will enable in-depth analysis. The TESS observing strategy will lead to high-enough frequency resolution to see temporal variations in the additional (probably non-radial) modes. For Cepheids, only a few cycles will be observable in general, so our strategy is to select the shorter period ones to be observed with the 2-min cadence.

Quality of TESS data

As TESS will mainly observe bright RR Lyrae stars and Cepheids in the 9-10 mag range, it is expected that the quality of the photometric measurements will be comparable to that of Kepler, which mainly observed RR Lyrae stars in the 14-16 magnitude regime. Although it will be possible to analyze fainter objects in the Full Frame Images, for this specific proposal we set a magnitude limit of 12 to ensure that bright and high SNR targets are proposed for 2-min observations. For a few proposed bright Cepheids (magnitude range of 2-8) even better quality data are expected.

For our targets, crowding is not an issue, despite the large TESS pixel size, since our targets are high amplitude pulsators (with an amplitude of 0.5-1.5 mag). Therefore we will be able to detect (and disentangle) the variation unambiguously.

Science Case

RR Lyrae stars play an important role in astrophysics as standard candles, tracers of old stellar populations and touchstones for stellar pulsations. Thanks to the recent sky surveys, the number of known RR Lyrae stars now reaches a hundred thousand in our Galaxy, and their distribution reveals more and more structures in the halo of the Milky Way. Simultaneously, photometric space missions, such as MOST, CoRoT, and especially, Kepler and K2 reinvigorated the study of RR Lyrae pulsations. These stars, assumed to be simple pulsators only a decade ago, turned out to be intricate dynamical systems. Continuous high-precision observations revealed cycle-to-cycle variations, millimagnitude-level additional modes, and their apparent connection to the modulation of some RR Lyrae stars known as the Blazhko effect. While theoretical works gave an explanation to some of these new effects, many others are not yet understood.

While these missions have greatly expanded our knowledge, they provided relatively small fields-of-view. Most RR Lyrae stars are far away from the Sun, hence most of the observed ones are faint and hard to follow-up from the ground. With TESS, we can focus on the nearest few hundred stars that are distributed relatively uniformly on the entire sky.

Although the cadence of the Full Field Images is sufficient for an overall view of the pulsation properties of RR Lyrae stars, we selected a small subsample of the brightest and most interesting stars for a more detailed study. The short cadence mode is required to study the following topics:

(1) RR Lyrae stars have fast and/or sharp features in their light curves, such as the bumps caused by shock waves reaching the stellar surface. We know that these features vary with the Blazhko effect and are affected by the mode interactions. Shorter cadence is especially important for resolving these features in overtone stars that have shorter periods down to 4-6 hours. The 2-minute cadence observations provide us with **unprecedented views on the interaction between pulsation, modulation, and the dynamics of the stellar envelope and convective zone**.

(2) We need **well-sampled extrema of the pulsation cycles** to investigate non-linear phenomena, cycle-to-cycle variations and temporal behavior of period doubling. Shorter cadence is especially important for resolving these features in overtone pulsators that have periods down to 4-6 hours. In addition, we can address the stability of the light curves and search for signs of pulsation jitter via O-C methods. Short cadence provides **more accurate O-C diagrams that could uncover small temporal deviations.**

(3) The **amplitude distribution of the harmonics** of RR Lyrae stars is poorly known and is not understood. Some RR Lyrae stars show power excess (others show minimum) in the high-frequency harmonics of the dominant pulsation mode that can be resolved with short cadence only. The origin of this feature is unknown, and further observations are highly desirable to better understand the light curve shape details of these objects, hence providing more constraints on the dynamics of their atmosphere.

Just as RR Lyrae stars, Cepheids are also fiducial astrophysical objects. They used to be considered as regular pulsators. However, additional modes, period doubling and most recently **short-lived X-ray flashes** have been discovered at well-defined pulsational phases based on XMM and Chandra observations. This phenomenon has never been monitored simultaneously in the optical passband. TESS provides a unique opportunity to look for the optical counterpart of this intriguing characteristic. Light curve irregularity is another observational result, the physical cause of which is poorly known. With TESS, we can address this problem by observing a large sample of bright Cepheids scattered all around the sky. In order to meaningfully study these phenomena, good time resolution is needed.

Priorities of targets

Our target stars fall into the following categories:

- ***RR Lyrae, the prototype*****:** Short cadence observations with Kepler revealed intricate and unexpected details that are in need of follow-up, this time with extended simultaneous ground-based observations. Based on Kepler data, its Blazhko-cycle almost completely disappeared, **now it is recovering**. A revisit will help to clarify its temporal behavior.
- ***Bright first-overtone (RRc) stars*****:** we selected seven modulated and six non-modulated stars. The list includes stars with large period variations (although on longer timescales), and the peculiar star MT Tel. The latter is one of the small number of stars that fall into **the transition region in between RRab and RRc stars in the relative Fourier parameter planes.** Observations of the detailed light curve properties, such as the stability of the mode(s) will undoubtedly advance our understanding of normal and peculiar overtone pulsators alike.
- ***Modulated RRc stars*****: Our knowledge about the Blazhko effect in RRc stars is considerably more limited than that of the fundamental-mode stars,** given the low occurrence rate of both the RRc stars and the modulation among them. The selected stars have short Blazhko periods, therefore we can cover multiple modulation cycles in a single pointing. **The short cadence of TESS allows us a rare opportunity to follow the changes in the light curves of modulated RRc stars.**
- ***Bright double-mode (RRd) stars*****:** Very few RRd stars have been observed by space telescopes, despite their rich spectrum of dynamical phenomena (modulations, additional modes). Therefore, we included two bright representatives.
- ***Bright fundamental-mode (RRab) stars*****:** we selected 14 RRab stars with stable light curves and 14 with Blazhko modulation. We gave preference to Blazhko stars with short modulation period and those with complex light-curve variations (double modulation, modulation with changing strength). Among RRab stars with stable light curve there are stars that are binary candidates and stars showing dynamical phenomena (humps, bumps).
- ***Cepheids with X-ray flashes:*** For Delta Cephei, there are positive X-ray flash observations, while for Polaris and V473 Lyr the observations are underway.
- ***Short-period Cepheids***: Observations of short-period Cepheids, including double-mode Cepheids, prototypes of Anomalous Cepheids (XZ Cet) and Type II Cepheids (BL Her) will allow us to search for quick, short-lived phenomena, that other space missions are/were less equipped to do.

We added the largest priority to RR Lyrae, the prototype. The first 25 stars are our high-priority targets, consisting of representatives of various RR Lyrae and Cepheid subgroups, with emphasis on overtone RR Lyrae stars that have the shortest pulsation periods. The high-priority list also includes six targets (XZ Dra, ST Pic, UV Oct, XZ Cyg, RX Eri, RS Boo) that are considered for time calibration purposes and are proposed in cooperation with WG#0. As a minimum, we would like to have 2-min observations of at least one representative of every subtypes (modulated and non-modulated RRab, modulated and non-modulated RRc, RRd, binary candidate). The rest of the list was compiled in a way that if a cut is applied then still as many diverse targets are observed, as possible.

Ground-based support

We plan to complement the TESS observations with simultaneous multicolor photometry and spectroscopy on both hemispheres (some of our targets have been already monitored regularly):

- Piszkés-tető, Hungary, all-sky Fly's Eye camera (http://flyseye.net)
- Piszkés-tető, Hungary 1m RCC and 0.6-m Schmidt camera, BVRI, griz filters, spectrograph
- SPIRIT remote-controlled telescopes, Australia (35 and 43 cm, BVR-clear-Halpha filters, http://spirit.icrar.org/)
- San Pedro de Atacama, Chile, 40-cm f/6.8 Optimized Dall-Kirkham + CCD FLI + BVI
- Astronomical Centre Lajatico, Italy, 0.3m Newtonian f/3.9 + CCD G2-1600 + BVRI
- Observatory Znojmo, Czech Republic, 0.2m Schmidt-Cassegrain f/10 + CCD G2-0402 + BVRI
- Masaryk University Observatory, Czech Republic, 0.6m Newtonian f/4.5 + CCD G4-16000 + BVRIbvy filters
- Remotely operated 0.15 Newtonian f/5 telescope + CCD G2-1600 + BVRI from the Czech Republic
- Lulin Observatory, Taiwan, SLT 40cm Telescope with Andor 936 CCD (BVRI and griz filters)

List of uploaded stars with remarks:

Name	TIC	TESSmag	Type	Remarks
RR Lyr	159717514	7.46	RRab	prototype, changing Blazhko, additional modes
MT Tel	143765469	8.72	RRc	peculiar LC shape
V701 Pup	156465251	10.29	RRc-BL	strong amplitude variations
TV Boo	168709463	10.68	RRc-BL	
XZ Dra	229913521	9.87	RRab-BL*	binary candidate, CVZ
ST Pic	150166721	9.00	RRab	CVZ
FW Lup	148598686	8.39	RRab	metal-rich
Delta Cep	415741355	3.53	DCEP	X-ray flashes,

V473 Lyr	403786081	6.08	DCEP	prototype second overtone, modulated, period doubling
ASAS090900-0410.4	280799052	10.58	RRc-BL	
SW And	437761208	9.29	RRab-BL	
alpha UMi	303256075	1.37	DCEP	low-amplitude variation
RV CrB	236392102	11.02	RRc-BL	strong period change
XZ Cet	423761480	10.05	ACEP	double maximum anomalous Cepheid
CS Eri	142240683	8.79	RRc	
BL Her	310927519	9.91	T2Cep	Type II Cep prototype
AC And	24658137	10.21	ACEP?	triple mode pulsator
UV Oct	291451813	9.14	RRab-BL	
XZ Cyg	267808239	9.62	RRab-BL	possibly longer coverage
RX Eri	114923989	9.37	RRab	
RS Boo	409373422	9.73	RRab-BL	complex modulation
V823 Cas	406894356	10.30	ACEP?	triple mode pulsator
DM Cyg	117638854	11.02	RRab-BL	short BL period
RZ Cep	455896112	8.84	RRc	period changes
TU UMa	144376546	9.44	RRab	binary candidate
DH Peg	415738730	9.39	RRc	
RU Scl	313935068	9.57	RRab-BL	short BL period
SS For	72636949	10.06	RRab-BL	
V372 Ser	38947200	10.80	RRd	
V500 Hya	62455702	10.42	RRd	
SV Hya	453469791	10.10	RRc	period changes
RU Psc	80514329	9.79	RRc-BL	
LS Her	105769104	10.67	RRc-BL	complex modulation, very short pulsation period
AH Cam	73017653	10.74	RRab-BL	short BL period
ASAS200431-5352.3	101433435	10.77	RRc-BL	
RR Leo	3941985	10.40	RRab	binary candidate
SU Dra	142848794	9.66	RRab	binary candidate
AV Peg	257957574	10.10	RRab	binary candidate
X Ari	365368501	8.88	RRab	binary candidate
T Sex	275254541	9.88	RRc	

V1334 Cyg	373202340	5.71	DCEP	binary CEP
UY Eri	9846652	11.71	ACEP	uncertain class, peculiar
SU Cas	408574766	5.43	DCEP	binary Cepheid
V371 Per	238737310	10.22	DCEPB	shortest period FM/O1 beat Cep
V363 Cas	83902335	9.50	DCEPB	shortest period O1/O2 beat Cep
BV Aqr	206460831	10.55	RRc-BL	strong period change
S Ara	381559060	9.95	RRab-BL	wavy period change
CO Aur	400100492	7.00	DCEPB	O1/O2 beat Cep
AU Peg	279587090	8.59	T2CEP	binary, cycle-to-cycle changes
VY Pyx	410163960	6.60	T2CEP	
LP Cam	84440140	10.44	RRab	strong hump
RZ CVn	173105394	11.30	RRab-BL	complex Blazhko modulation
VX Her	356085581	10.27	RRab	Blazhko and binary candidate
IK Hya	98991911	9.81	RRab-BL	complex modulation
V971 Aql	99622912	11.23	T2CEP	well-known Type II Cepheid
V553 Cen	47887139	7.82	T2CEP	C-rich Cepheid
RT TrA	324935946	8.97	T2CEP	C-rich Cepheid
TT Lyn	29172806	9.32	RRab	stable RR Lyr
RZ Lyr	68554074	11.22	RRab-BL	double modulation binary candidate
BH Peg	456832557	10.01	RRab-BL	uncertain modulation period binary candidate
AR Per	410137462	9.74	RRab	Blazhko suspect
BB Vir	339541239	10.91	RRab	Blazhko candidate, binary candidate
XX Vir	6030027	11.78	T2CEP	uncertain class, peculiar
FF Aql	311218292	4.71	DCEP	binary CEP
Y Car	457801419	7.34	DCEP	binary CEP

*BL: Blazhko-modulated