TESS Proposal on behalf of TASC WG 5

Asteroseismology of Main Sequence OB classical pulsators

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Abstract

The main aim of this proposal is to solve uncertainties in the modelling of stars located in (or near) the upper main sequence (OB-type stars) by using asteroseismic techniques. As TESS is the only mission that will enable us to gather the data needed to arrive at a consistent picture for all massive stars in the near future, we request to observe a carefully selected sample of 955 β Cephei stars (for in-depth asteroseismic studies to obtain a global characterisation of these pulsating stars), 94 O dwarf stars (all-sky) and 134 OB stars in the Southern Continuous Viewing Zone (for the detection of their theoretically predicted pulsations), and 10 Maia variables (to confirm or refute the apparent pulsations that are not predicted by theory).

Science Case

It is still a long way to a solid understanding the structure and evolution of hot massive stars, the building blocks of their host galaxies. Essential uncertainties in their modelling comprise:

- Rotation and angular momentum evolution. Rotation influences the evolution of massive stars as strongly as mass and metallicity (e.g., see Maeder 2009, Physics, Formation and Evolution of Rotating Stars. Berlin: Springer). Rotation reduces the stellar luminosity, increases the central density and a reduces the central temperature, i.e. rotating stars have a reduced effective mass. Angular momentum transport from the core to the envelope in massive stars is needed to avoid that their iron cores in later evolutionary stages reach critical rotation.
- Internal mixing and main sequence lifetime. Internal mixing causes surface abundance changes during stellar evolution (e.g., Maeder 1987, A&A 178, 159). Mixing of material into the hydrogen-burning stellar core ("convective overshooting") considerably affects the main sequence lifetimes of massive stars (e.g., Mowlavi & Forestini 1994, A&A 282, 843).
- Opacities. With the "new" solar abundances (Asplund et al. 2004, A&A 417, 751) an increase in the heavy-element opacities in the Sun is required to match helioseismic data. The same conclusion holds for pulsational mode excitation in massive stars (e.g., Lenz 2012, arXiv:1206.2147). It is also unclear which of the presently available opacity tables are preferable to model hot massive stars as a whole (Walczak & Daszyńska-Daszkiewicz 2010, AN 331, 1057).
- Binarity. Some 30% of young massive stars stem from binary interaction (de Mink et al. 2014, ApJ 782, 7). They may be the reason for an overpopulation of massive post-main sequence stars (Fitzpatrick & Garmany 1990, ApJ 363, 119), and are neutron star and black hole progenitors.

These essential problems can be addressed, and likely solved, using asteroseismology. For massive pulsating stars, such as the β Cephei stars, this has been demonstrably applicable (e.g., Dupret et al. 2004, A&A 415, 251; Pamyatnykh et al. 2004, MNRAS 350, 1022), as constraints on the convective core size, heavy element abundance and differential interior rotation were derived. However, to arrive at a consistent picture for all massive stars, more objects in a wide mass range must be seismically sounded. The underlying measurements must be of the highest precision and have recently become available mostly due to photometric space missions, leading to in-depth seismic investigations for many classes of pulsating stars. However, this progress did so far not involve OB stars (with the exception of Slowly Pulsating B stars, e.g. Triana et al. 2015, ApJ 810, 16) to a similar extent. The original Kepler field comprised very few such stars. Also the K2, MOST, CoRoT and BRITE missions have observed very few of them, partly with considerably poorer accuracy. TESS' high-quality variability study of the whole sky is expected to change this picture completely and will therefore be a unique - perhaps the only - opportunity to acquire data of the necessary quality to perform seismic studies of a large sample of OB stars.

In this proposal, we concentrate on three groups of OB stars. First, we want to conduct a survey for theoretically predicted pulsations in O dwarf stars (Moravveji 2016, MNRAS 455, L67), potentially opening up another class of stars for seismic sounding - the most massive ones to date. Second, we want to observe as many β Cephei stars as possible, to be able to perform in-depth asteroseismic studies, individually or as a group (cluster and association members). Third, we would like to solve the 60-year old enigma of the Maia variables, stars between the SPB and δ Scuti instability strip that apparently pulsate but according to theory should not. If Maia variables exist - and evidence is that they do - the physics of stellar envelopes of late B stars needs to be revised (e.g., Balona et al. 2015, MNRAS 451, 1445).

The need for 2-min cadence

The targets related to our working group have overall variability time scales that could in most cases be well sampled with 30-min FFI cadence. However, some do exhibit phenomena occurring on shorter time scales that will be at least severely smeared out at such a cadence:

- One of them is the "stillstand phenomenon" in the light curves of some high-amplitude pulsators (e.g. Sterken et al. 1987, A&A 177, 150).
- Another one is the claimed presence of short-time scale "stochastic" oscillations (e.g. Belkacem et al. 2009, Science 324, 1540) whose investigation requires 2-min sampling.
- The third are the theoretically predicted pulsations in O stars that have time scales as short as one hour. The initial list of O-stars was selected from the Galactic O star catalog (http://ssg.iaa.es/en/content/galactic-o-star-catalog/; Maíz Apellániz et al. 2013, Massive Stars: From alpha to Omega, 198) which comprises about 600 Galactic O stars. For the final list, we only focus on those classified as dwarfs, since these are the targets in which the 2-min cadence is more critical due to the predicted type of variability (high frequency pressure modes combined with stochastic modes). For the other O-type stars (giants and supergiants), the 30-min FFI cadence should be enough. Although these later targets are also expected to be affected by stochastic variability, they are also predicted to pulsate in pressure and gravity modes with somewhat larger periods.
- Finally, some Maia variables have been reported to show periods shorter than one hour (Lehmann et al. A&A 312, 508; Kallinger et al. 2004, IAUS 224, 848).

Even though it will probably be possible to study variability in excess of the Nyquist frequency with TESS data, the severe amplitude reduction caused by integration times of the same order as the variability time scale will seriously hamper the study of these phenomena. Although it is difficult to predict which particular stars would show the above mentioned rapid variations (and we thus must take chances), we have attempted to assign a higher priority to such objects.

Length of time series

A 27 days-long run should be long enough to resolve most modes excited in β Cephei stars. However, the longer a run, the better. Indeed, longer observations will lead to a lower detection threshold and a better frequency resolution (a few stars of this type have beat periods longer than 27 days), and it will allow for the study of amplitude and/or period changes. In addition, with longer runs, it may become possible to study binarity of some stars by means of the light-time effect. For the O dwarf stars and Maia stars, the length of the time series will be less critical as the primary goal is the detection of pulsations, although seismic studies based on individual mode frequencies are also intended.

Quality of TESS data

Expected noise level

According to the current information, the expected quality of TESS data should be comparable to Kepler data for stars that are 5 magnitudes brighter. We have examined the Fourier noise level in the periodograms of some “constant” or easy-to-prewhiten Kepler target light curves with respect to their magnitude (Fig. 1). According to this, for a target with a TESS magnitude brighter than 2.5 we can expect a noise level of 1 ppm, for a star with TESS mag = 7.5 a 10 ppm noise level, and for TESS mag = 12.5 the noise level will increase to 100 ppm.

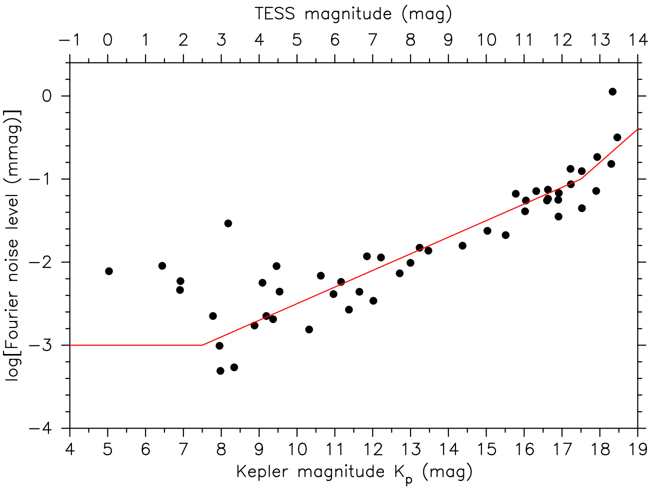

Figure 1: Fourier noise vs. Kepler magnitude for a number of Kepler targets. Length of time series 27 d.

Magnitudes of our targets

Given that they are intrinsically luminous, most of our target stars are also apparently bright, which is an advantage for TESS observations. Some 150 stars have a TESS magnitude brighter than 7.5, i.e. TESS observations will yield a Fourier noise level of 10 ppm or better. For some 980 (i.e. about 80%) of our stars we can expect a < 40 ppm noise level in their periodograms. This is some six times lower than ground-based observations would be capable of. Outside of the CVZ have only four stars fainter than $mag_{TESS} = 12.0$, whereas in the CVZ we can go 1.4 mag fainter to reach the same Fourier noise level.

Amplitude reduction in the red TESS passband

Our targets will be among the hottest/bluest ones observed by TESS. Therefore it is important to check how their expected pulsation amplitudes compare to visual ones. Such a comparison (based on the method by Balona & Evers 1999, MNRAS 302, 349, who use stellar model atmospheres to predict amplitude ratios between various filter passbands theoretically) is shown in Table 1, for one example Maia star (2.5 $M_\odot$ model), one example β Cephei star (10 $M_\odot$ model), and one example O dwarf star (25 $M_\odot$ model). As it can be seen, the amplitudes in the TESS passband are not dramatically lower than visual ones (the hotter a target, the smaller the amplitude loss), because both passbands are located in the Rayleigh-Jeans tail of the stellar energy distribution. As a matter of fact, these amplitude ratios are significantly distinctive to even allow a (partial) mode identification for some pulsators!

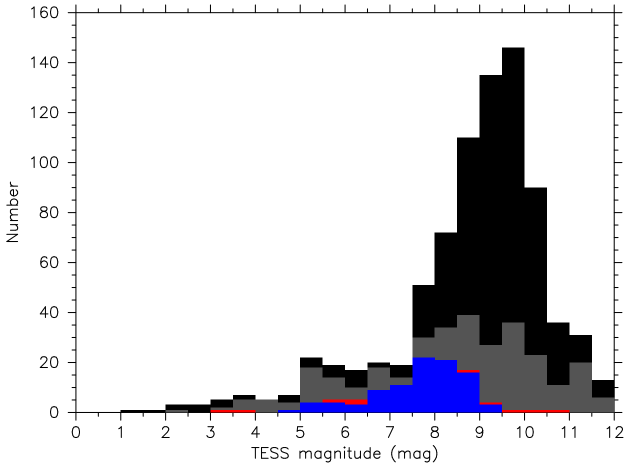

Figure 2: Distribution of the TESS magnitudes of our target stars. O dwarf stars are shown in blue, Maia stars in red, β Cephei stars in black, and β Cephei candidates in grey.

Table 1: Theoretically predicted amplitude ratios between the Johnson V filter and the TESS passband for different pulsation modes of the different types of stars in this proposal.

Model	2.5 $M_\odot$	10 $M_\odot$	25 $M_\odot$
$A_{TESS}/A_V(l=0)$	0.825	0.854	1.033
$A_{TESS}/A_V(l=1)$	0.831	0.894	1.012
$A_{TESS}/A_V(l=2)$	0.834	0.916	0.989
$A_{TESS}/A_V(l=3)$	0.661	0.715	0.764
$A_{TESS}/A_V(l=4)$	0.956	1.009	1.035

Prioritization of targets

Given the above considerations, each individual target from the β Cephei lists has been assigned a score according to stellar brightness (= inverse of expected Fourier noise level, cf. Fig. 1), variability amplitude, seismic potential of the star (= number of known oscillation modes), ecliptic latitude (= expected length of time series), and inverse of amplitude reduction in 30-min binning. These different scores were multiplied and the stars accordingly ranked. Note that this procedure also favours stars with good possibilities for ground-based follow-up/support: bright stars for spectroscopy and high-amplitude stars for multicolour photometry. A few stars with particularly high scientific interest (e.g. available mode identifications, runaway stars) were manually moved up the list. For the O dwarf stars and Maia stars we did not use the (in most cases unknown) amplitude and number of oscillation modes, and only ranked according to brightness and ecliptic latitude. For the OB stars in the CVZ brightness was the only criterion.

The four lists were merged considering that the number of targets they contain are very different. There are 10 Maia candidates, 94 O dwarf stars, 134 stars in the CVZ, and 955 β Cephei stars (of which 388 are candidate members, which are at the very bottom of the target list). We therefore started with the highest-ranked Maia star, followed by the first O dwarf star, the first β Cephei star, the first CVZ stars, then the second Maia star etc. This assures that the science cases requiring less stars do not become discriminated against.

Our combined target list therefore currently comprises 1193 unique objects, a 46% increase to the 819 stars submitted in the first round. The reason is the inclusion of the CVZ objects, and our continued search for β Cephei pulsators in ground-based surveys (see below). To reach our minimum science goal, we estimate that the top 400 stars of this list would require TESS observations in 2-min cadence.

Ground-based observations in relation to this proposal

Two thirds of the proposed β Cephei stars have not been known in the past. They originate from a data mining effort within WG5, where the KELT, ASAS, HATnet and OGLE data bases were searched for such variables. Whereas a large majority of these stars should have been classified correctly, follow-up will be carried out.

We shall provide high-resolution spectroscopy with HERMES@1.2-m/Mercator (La Palma), FIES@2.56-m/NOT (La Palma) and SONG@1-m/Hertzsprung (Tenerife) within the IACOB project (http://www.iac.es/proyecto/iacob/; Simón-Díaz et al. 2015, Highlights of Spanish Astrophysics VIII, 576), and classification spectroscopy with an in-house telescope and dedicated spectrograph in Brno. We can also reach for ESO, SAAO or ING facilities for additional follow up. The purpose of our general ground-based spectroscopy is radial velocity monitoring to detect binarity, identification of Be stars, and determination of the basic parameters like effective temperature, surface gravity and projected rotational velocity. Together with the TESS data, this shall provide an in-depth study of these pulsators as a group.

We plan time-series ground-based spectroscopy and multicolour photometry for some selected targets, not necessarily simultaneously with TESS. These measurements will be used to obtain stellar parameters and pulsational mode identifications. The involved telescopes are listed here:

Northern hemisphere:

- 0.75-m APT (Arizona, 9 months per year; multicolour photometry; no competition; 2016-2020)
- 0.6-m telescope (Brno, in-house telescope; classification spectroscopy)
- 1.2-m Mercator telescope (La Palma, high-resolution spectroscopy; guaranteed time + IACOB project)
- 2.56-m NOT (La Palma, high-resolution spectroscopy; IACOB project)
- 1-m Hertzsprung/SONG (Tenerife, high-resolution spectroscopy; IACOB project)
- 4-m LAMOST (Xinglong, low-resolution spectroscopy)

Southern hemisphere:

- 0.75-m APT (SAAO, South Africa, 3 months per year; multicolour photometry; some competition; 2016-2020)
- 0.5-m telescope (Bloemfontein, South Africa, 3 months per year; multicolour photometry; some competition; 2018-2020)

Distribution of our stars in the sky

Since our targets are young objects, most of them are located very close to the Galactic plane. One may think that this gives rise to severe crowding problems, but due to the intrinsic brightness of our targets this is not really an issue: only about 3.5% of them would have companions that add significant ($\approx$ 10%) flux to the TESS pixels containing our targets, mostly those in the central regions of open clusters.

The concentration of our targets in the Galactic plane implies they are quite unevenly distributed over the ecliptic plane as well. In addition, 65.5% of our targets are located South of the ecliptic plane. Our targets will therefore not be evenly distributed over the different TESS fields: for most pointings we will have few targets, but for a few others - those of highest interest to us - we will have many more than the all-sky average. We would highly appreciate if this was kept in mind during the overall TASC target allocation.