High precision monitoring of fast photometric variability in evolved compact stars with TESS

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Abstract: Intermediate (post-RGB) and ultimate stages of stellar evolution for initially low mass stars (including our Sun) harbor a wealth of variable evolved compact objects. These are distributed along the pre-white dwarf and white dwarf cooling tracks, as well as within the so-called Extreme Horizontal Branch (EHB) and post-EHB phases (also known as hot subdwarf stars). In particular, several groups among these stars develop short-period non-radial oscillations opening invaluable windows on their internal structure and dynamics through the use of asteroseismology. TESS will permit an efficient and nearly exhaustive high precision monitoring from space of the brightest known stars belonging to these classes, most of them only having photometric data gathered from the ground so far.

Cadence: This target list is for the 20s-cadence mode

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Science case: The late stages of evolution for initially low to intermediate mass stars (including our Sun and $\sim 98\%$ of all stars in the Universe) harbor several groups of rapidly pulsating compact stars that can be probed deeply with asteroseismology. This includes in particular pre white dwarf and white dwarf pulsators found in 3 main flavors as they cross the *GW Vir* (DOV), *V777 Her* (DBV), or *ZZ Cet* (DAV) instability strips while cooling down. Other groups of white dwarf variables have also recently been identified, suspected, or predicted, adding further asteroseismic potential to an already rich situation (see Figure 1 and, e.g., the review from Fontaine & Brassard 2008, *PASP*, **120**, 1043). The oscillation modes detected in pulsating white dwarfs are typically low degree ($\ell = 1$ and 2), low-to-mid radial order g-modes with periods ranging from a few minutes to about half an hour. Their periods are sensitive to the global stellar structure, internal chemical stratification, and rotation, as demonstrated by many authors in the field, either recently or over the past years. Compact pulsators are also found among intermediate stages of evolution following the Red Giant Branch. Such stars populate the so-called Extreme Horizontal Branch and beyond, and are commonly referred to as hot subdwarf stars (of spectral type sdB, sdOB, or sdO). Rapid p-mode non-radial oscillations on timescales ranging from ~ 40 s to a few minutes have been found both in sdB stars (the *V361 Hya* pulsators; named sdBVp in Figure 2) and more recently in sdO stars. Hot B subdwarfs also host another group of slow $g-$mode pulsators with periods of $\sim 1-4$ hours (the *V1093 Her* pulsators; see again Figure 1 and the review from Heber 2016, *PASP*, **128**, 2001). *All these classes of pulsators play a fundamental role for strenghtening our understanding of the late phases of stellar evolution.*

They open invaluable seismic windows on the internal structure and dynamics of objects representative of the late stages of the life of most stars, thus providing a unique opportunity to investigate deeply the physical processes shaping their interior over time: Are nuclear rates, in particular related to helium burning and C/O production, accurate? Are convective helium burning cores well understood and accurately modeled over the entire horizontal branch phase? What is the extent and impact of overshooting and semi-convection at the edge of these cores? How do these stars rotate internally and at which rate? Does rotation affect their structure through extra mixing processes? How many thermal pulses post-AGB stars undergo before settling down on the white dwarf cooling sequence? How should we modify our current models to better match the observed pulsation modes and how does it affect our present knowledge on stellar evolution? How convection influences stellar pulsation in different parts of the instability strips? What is the origin of temporal amplitude and frequency variations in compact pulsators? All these questions, among others, can be addressed with asteroseismology of compact pulsators provided that extended sets of high quality seismic data become widely available for these stars. Moreover, for the compact pulsators near the ecliptic poles with longest coverage, it will also be possible to detect low-mass companions down to planetary masses by searching for binary signatures in their amplitude spectra, using the frequency modulation and phase modulation (O-C) methods.

TESS all sky photometric survey has a central role to play in exploiting globally this seismic potential since, for the first time and contrary to former space observations much more limited in terms of sky coverage, high precision photometry of continuous duration for almost all of the brightest identified stars belonging to these classes of pulsators become possible. This will ensure that state-of-the-art asteroseismic data obtained from space become widely available to feed modeling efforts in the field. *The large increase of the number of compact pulsators having ultra high precision seismic data as a result of TESS observations will strongly improve our capacity to draw a complete, statistically meaningful picture of the ultimate stages of stellar evolution.* Overall brighter objects, compared to pulsators already observed with KEPLER or K2, will also mean better opportunities for follow-up ground based projects to pin point more accurately the properties of these stars.

The timescales for the light modulations involved in these fast pulsators clearly require that the fast 20s cadence mode is used for the monitoring. We have estimated with dedicated simulations (from S. Murphy) that the amplitude smearing induced by using the longer 2-min cadence would be unacceptably large (up to $\sim 80\%$ for the shortest periods) in a context where our targets are already quite faint and the bandpass of TESS is not optimal for our purposes. Moreover, we found that in most cases it would not be possible to resolve the Nyquist ambiguity in case some frequencies are above the Nyquist limit, which would likely occur quite often with the 2-min sampling.

Length of time series: For all stars associated to this proposal, we request the longest possible time series permitted by the ecliptic latitude of each object considered. Asteroseismology greatly benefits from an extended time baseline both in terms of overall signal-to-noise achieved in Fourier space (a factor 3 improvement expected from 27d to 1yr) and in frequency resolution (a factor 10 improvement between 27d and 1yr). In particular, pulsating B subdwarf stars are generally slow rotators with periods ranging from a few days to several weeks. A longer time series when possible could therefore quite often resolve the star's rotation while a 27d lightcurve would not.

Quality of TESS data: Almost all of the proposed targets only have ground based fast photometric data available, sometimes limited to the original (and usually short) discovery lightcurve. For these stars, TESS observations will outperform any available time series on the basis of at least 27d of coverage without interruption, which is simply not feasable from the ground. In terms of signal to noise, we expect the TESS data to be roughly equivalent to KEPLER data obtained for stars 5 magnitudes fainter. As an illustration, Figure 3 shows the data quality obtained for a 18.2 mag ZZ Ceti star monitored for 31 days with KEPLER (hence equivalent to a 13.2 mag star observed with TESS for about a month). Oscillations are very clearly detected. Besides, pulsating white dwarfs down to magnitude 19 and above have successfully been observed with K2, suggesting that TESS can provide useful data at least down to magnitude ~ 15. We considered in this proposal objects down to mag ~ 16 in order to be as inclusive as possible in regard of the true performances of the instrument that will be more precisely evaluated after the first observation. In this context, we note that typical mode amplitudes observed in pulsating white dwarfs and $p-$mode sdB pulsators can reach up a few percent of the mean brightness of the star (in B or V-band). However, with the redder TESS bandpass, we can expect somewhat reduced amplitudes affecting mostly ZZ Ceti stars. Figure 4 shows the number of targets depending on the magnitude limit we impose for the faintest observable objects.

Priorities: Priorities have been set mostly by order of increasing magnitude (brightest objects having highest priority). However a few specific objects have been moved upward in the list due to their outstanding intrinsic interest and/or their position relative to the ecliptic poles where they can be observed longer. We also provide, at a lower overall priority relative to well identified pulsators, a list of DAV, DBV, and DAOV candidates selected on the basis of their effective temperature and surface gravity estimated either from spectroscopy or from photometry.

Ground based observations: Observations are currently being carried out from Arizona (E.M Green) and South Africa (D. Kilkenny) to identify new bright p-mode hot subdwarf pulsators near the ecliptic poles. Moreover, identification spectra of objects with GALEX UV-excess near the southern ecliptic pole are being collected from RSS on SALT, in particular to discover more white dwarfs and subdwarfs (J.J. Hermes). Observations to further characterize TESS WG8 targets before launch and provide follow-up capabilities after launch are also planned from Konkoly Observatory (Zs. Bognar) and from Chile (M. Vučković).

Additional remarks: The list provided with this proposal is nearly complete but not final. It will be updated following the outcome of current ground based observations. We point out that a small fraction of the proposed objects were not found in the TESS Input Catalog and therefore do not have a TIC number.

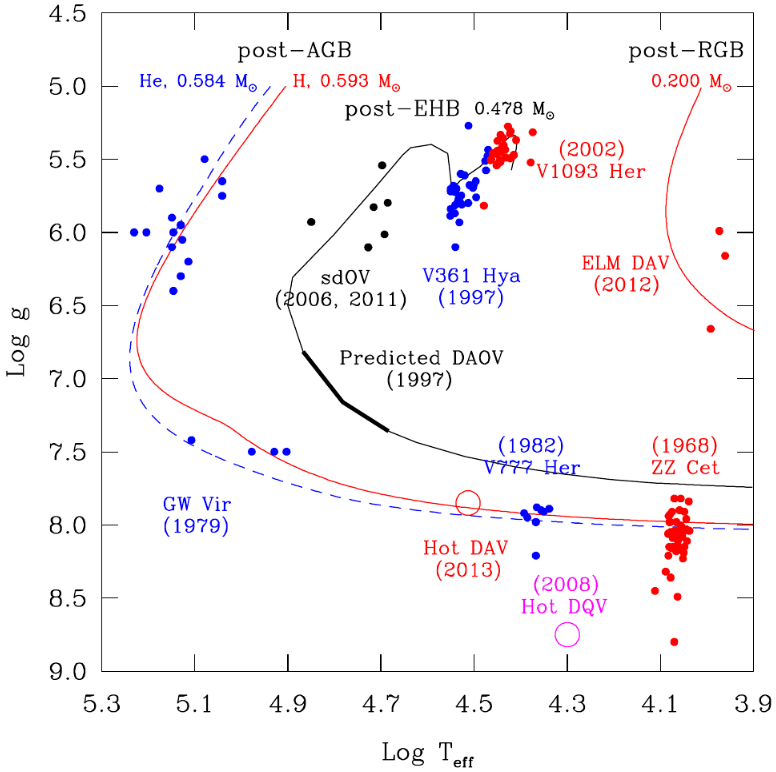

Figure 1: Distribution of the various classes of compact pulsators (with their discovery date) in the $\log g - \log T_{\rm eff}$ plane.

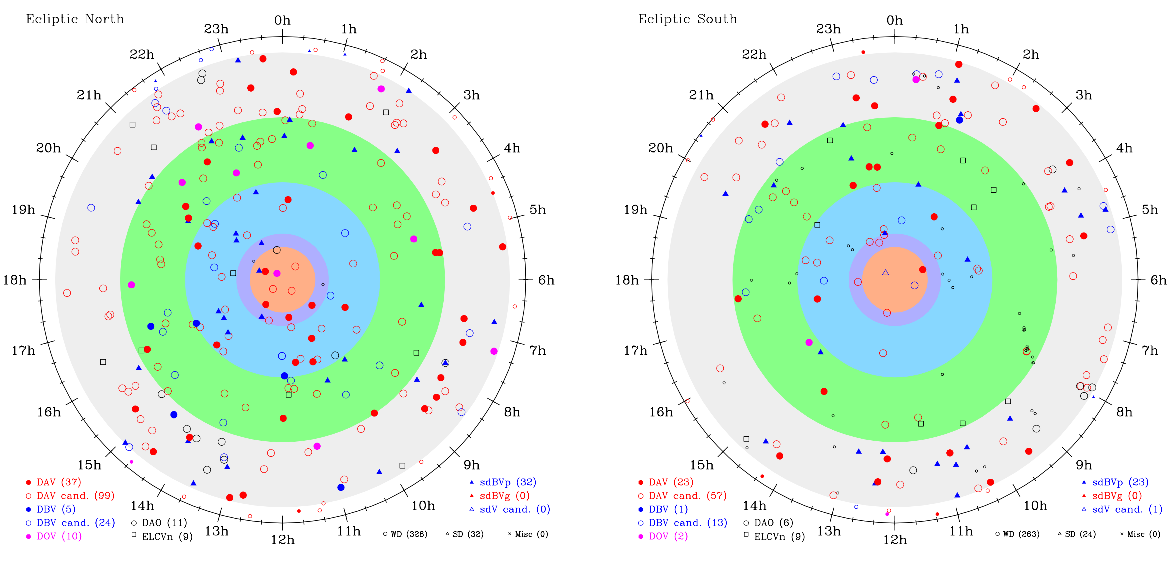

Figure 2: Distribution in ecliptic coordinates of all WG8 targets for the 20s-cadence mode. Left and right panels show polar projections of the Northern and Southern ecliptic hemisphere, respectively. The red, blue, and green regions roughly indicate the different zones in ecliptic latitude allowing for longer time series (see https://tasoc.dk/wg8 for further details).

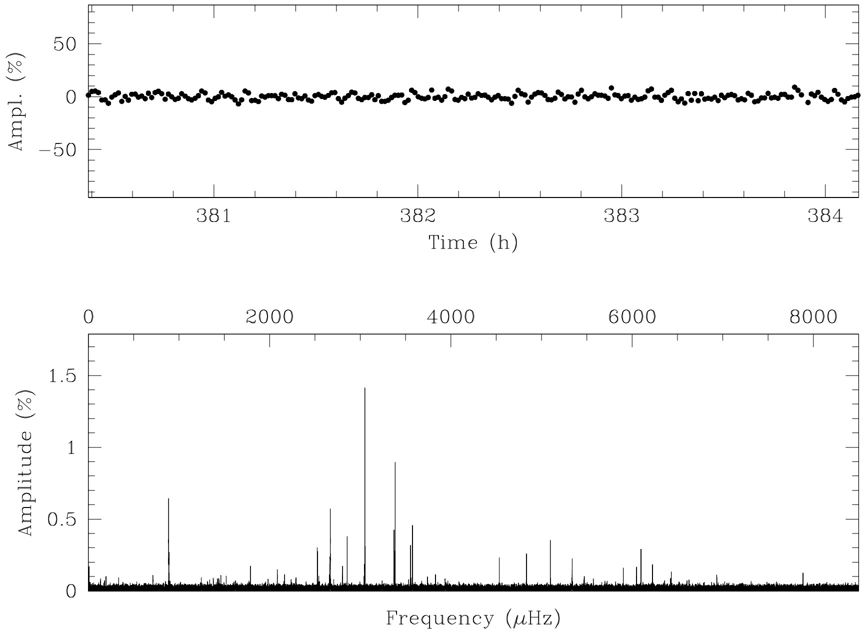

Figure 3: Lightcurve (top panel) and Lomb-Scargle periodogram (bottom panel) of the 18.2-mag DAV star KIC07594781 observed during 31 days by KEPLER. The noise level is 0.0175% (175 ppm) and the star shows modes with typical amplitudes from 1.4% to a few hundreds of a percent.

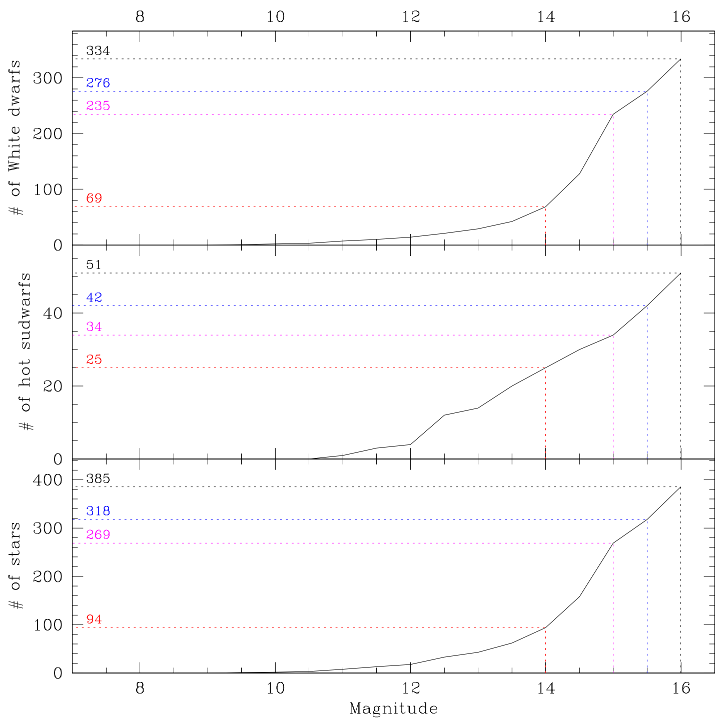

Figure 4: Cumulative number of WG8 targets for the 20s-cadence mode as a function of magnitude (bottom panel). Top and mid panels show the number of white dwarfs and hot subwarfs, respectively.