White-dwarf asteroseismology with the *TESS* space telescope

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Resumen / A medida que las estrellas enanas blancas se enfrían, atraviesan una o más etapas de inestabilidad pulsacional en modos g (gravedad), convirtiéndose en estrellas variables multiperiódicas. Los objetos que experimentan estos estados de inestabilidad pulsacional permiten a los astrónomos estudiar sus interiores a través de las técnicas astrosismológicas, como si ellos pudieran "ver" sus regiones internas analizando los espectros de períodos de pulsación. La astrosismología de enanas blancas ha experimentado avances extraordinarios en años recientes gracias a las observaciones fotométricas de calidad y continuidad sin precedentes provistas por misiones espaciales tales como *Kepler* y *TESS*. Estos avances en el monitoreo de enanas blancas variables han sido acompañados por el desarrollo de nuevos modelos estelares y técnicas para modelar sus pulsaciones. En el presente artículo, revisamos los hallazgos más importantes –hasta principios de 2022– acerca de estas fascinantes estrellas pulsantes alcanzados gracias a las observaciones ininterrumpidas de alta calidad de la misión *TESS*, aún en ejecución, teniendo en mente que habrá probablemente muchos nuevos resultados en el futuro inmediato derivados de este telescopio espacial único.

Abstract / As white-dwarf (WD) stars cool, they go through one or more stages of g(gravity)-mode pulsational instability, becoming multiperiodic variable stars. Stars passing through these instability domains allow astronomers to study their interiors through asteroseismological techniques, as if they could "look" at their interiors by analyzing the spectra of pulsation periods. WD asteroseismology has experienced extraordinary advances in recent years thanks to photometric observations of unprecedented quality delivered by space missions such as *Kepler* and *TESS*. These advances in the monitoring of variable WDs have been accompanied by the development of new stellar models and techniques for modeling their pulsations. In this article, we review the most outstanding findings –up to early 2022– about these fascinating pulsating stars made possible with the high-sensitivity and continuous observations of the ongoing *TESS* mission, bearing in mind that there will possibly be many more new results in the immediate future derived from this unique space telescope.

Keywords / stars: evolution — white dwarf — stars: interiors — stars: oscillations — asteroseismology

1. Introduction

The most frequent final chapter in the life's book of the stars consists in the white dwarf (WD) stage. Indeed, most stars in the Universe (those with initial masses below $\sim 10 - 11 M_\odot$; Woosley & Heger, 2015, including our Sun) will end their lives in the form of these hot, compact and degenerate objects that evolve basically by cooling, delivering to the interstellar medium their reservoir of thermal energy produced long time ago, during their prior evolution. A comprehensive review article focused on the origin and evolution of WDs is that of Althaus et al. (2010). WDs are extremely old objects, with typical ages in the range $1-10$ Gyr (1 Gyr $\equiv 10^9$ yr), and are found in a range of masses of $0.15 \lesssim M_\star/M_\odot \lesssim 1.25$, with an average value of $M_\star/M_\odot \sim 0.60$ (Tremblay et al., 2016). They are characterized by planetary dimensions, with stellar radii $R_\star \sim 0.01 R_\odot$, and thus the matter inside is highly compacted, the average densities being of the order of $\overline{\rho} \sim 10^6$ g/cm^3. The equation of state inside WDs is that of a highly-degenerate Fermi gas (Chandrasekhar, 1939), the hydrostatic equilibrium in their interior being provided by the pressure of degenerate electrons counteracting gravity. In particular, electron degeneracy is responsible for the counter-intuitive relationship between the stellar mass and radius, according to which the more massive the star, the smaller its radius. Also, since the mechanical properties of a WD are described by a Fermi gas of degenerate electrons, there exist a limit mass —the Chandrasekhar mass, $\sim 1.4 M_\odot$— beyond which the structure of a WD becomes unstable.

The number of identified WDs has risen enormously in the last few years. Ground-based observations, mainly with the spectral observations of the Sloan Digital Sky Survey (SDSS; York et al., 2000), have increased 15 times the number of known WDs (Kepler et al., 2019). Recently, Gentile Fusillo et al. (2021) presented a catalog of $\sim 359\,000$ high-confidence WD candidates selected from *Gaia* DR3.

WDs are currently being used as valuable tools to learn about the history of our Galaxy and stellar populations. Indeed, as nearly all stars become WDs after the exhaustion of their central H, WDs are representative of the age distribution of the vast majority of stars. There-

Sérsic Prize contribution

fore, they provide independent chronometers for the age and star-formation history of the Galactic disk (e.g. Harris et al., 2006), and halo (Isern et al., 1998) through *cosmochronology.* Furthermore, WD cosmochronology can be applied to Galactic globular clusters (Hansen et al., 2013) and open clusters (e.g. García-Berro et al., 2010) as well. WDs also are extremely useful to explore the evolution of planetary systems (see, e.g., Hollands et al., 2022). On the other hand, WDs provide us information about the past evolution of their progenitor stars and the chemical enrichment of the interstellar medium (Fontaine et al., 2001; Winget & Kepler, 2008; Althaus et al., 2010)

An extremely important property of WDs, observed serendipitously for the first time by Landolt (1968), is that they experience g-mode pulsational instabilities that make them variable stars at least in one stage of their evolution. The interior of pulsating stars can be studied through the tools of asteroseismology by exploiting the information encrypted in their frequency spectra (Unno et al., 1989; Catelan & Smith, 2015; Aerts, 2021; Kurtz, 2022). In the case of WDs, asteroseismology has become in recent years one of the most important tools to learn about their origin, evolution and internal structure, extending the reach of the traditional techniques of spectroscopy, photometry and astrometry (see Winget & Kepler, 2008; Althaus et al., 2010; Giammichele et al., 2017; Córsico et al., 2019; Córsico, 2020a). In order to carry out asteroseismic analyses of pulsating WDs, it is crucial to have available a sufficient number of pulsation periods. In the beginning, this was made a reality thanks to the Whole Earth Telescope (*WET*; Nather et al., 1990; Winget et al., 1991, 1994). For a decade or so, the difficult undertaking of detecting as many periods as possible has begun to be done through space missions. Space-based observations meant a revolution in the area of asteroseismology for many classes of pulsating stars, particularly pulsating WDs. As a matter of fact, during the nominal *Kepler* mission (Borucki et al., 2010) and its *K2* extension (Howell et al., 2014), 89 pulsating WDs were monitored, and the analyses of 35 of them have been published up to now (see Córsico, 2020b, for a complete account).

2. The *TESS* space mission

The successor to the *Kepler* spacecraft is the *NASA*'s Transiting Exoplanet Survey Satellite (*TESS*, Ricker et al., 2015). This space mission was launched on 18 April 2018 with a planned nominal duration of 2 years, and 15 years of extended mission, with the main goal of searching for exoplanets around bright stars. Through nearly continuous stable photometry, as well as its extended sky coverage, *TESS* is making outstanding contributions to asteroseismology. *TESS* has observed 200 000 brightest stars in 85% of the whole sky in 2019 and 2020 in the first part of the mission. This space telescope performs extensive time-series photometry that allows to discover pulsating stars, and, in particular, variable hot subdwarfs, WDs, and pre-WDs with mag < 16, with short (120 s) cadence. Starting in July 2020, it is now also observing in 20 s cadence. The activities related to compact pulsators, as WDs and subdwarf stars, are conducted by the *TESS* Asteroseismic Science Consortium (*TASC*), Compact Pulsators Working Group (WG8). Since pulsating WDs are multiperiodic, they require long, uninterrupted strings of data. In this sense, Bradley (2021) discuss the advantages of space satellite-based data compared to ground-based data. In the next section, we review the most outstanding findings –up to early 2022– on the various classes of pulsating WDs and pre-WDs, made possible with the *TESS* space mission.

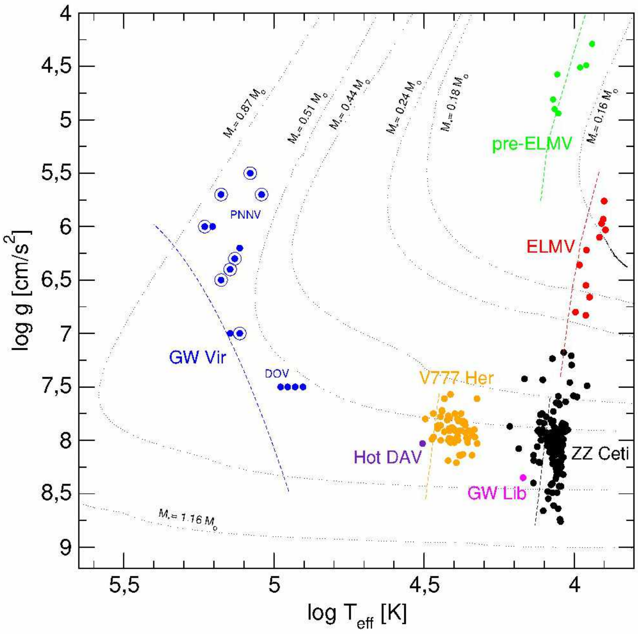

Figure 1: Representative subsets of the different families of pulsating WD and pre-WD stars (small circles of different colors) in the $\log T_{\rm eff} - \log g$ plane. GW Vir stars indicated with blue circles surrounded by blue circumferences are PNNVs. In the case of GW Lib stars, only the location of the prototypical object, GW Librae, has been included (magenta dot). Two post-VLTP (Very Late Thermal Pulse) evolutionary tracks for H-deficient WDs (0.51 and $0.87 M_{\odot}$; Miller Bertolami & Althaus, 2006), four evolutionary tracks of low-mass He-core H-rich WDs ($0.16, 0.18, 0.24$, and $0.44 M_{\odot}$; Althaus et al., 2013), and one evolutionary track for ultra-massive H-rich WDs ($1.16 M_{\odot}$; Camisassa et al., 2019) are plotted for reference. Dashed lines correspond to the location of the theoretical hot edge of the different instability strips.

3. Asteroseismology of WDs and pre-WDs with *TESS*

Pulsations in WDs and pre-WDs result in brightness variations in the optical and also in the ultraviolet (UV) and infrared (IR) regions of the electromagnetic spectrum, with amplitudes between 0.001 mmag and 0.4 mag. The luminosity fluctuations (with periods in the range $100 - 7000$ s) are likely induced mainly by changes in the surface temperature ($\Delta T_{\rm eff} \lesssim 200$ K) due to spheroidal nonradial g (gravity) modes (McGraw, 1979; Robinson et al., 1982) with low harmonic degree

($\ell = 1, 2$) and low and intermediate radial order (k). Nowadays, the number of known pulsating WDs and pre-WDs amounts to 606 (Córsico et al., 2019; Vincent et al., 2020; Guidry et al., 2021; Szkody, 2021; Lopez et al., 2021; Duan et al., 2021; Sowicka et al., 2021; Romero et al., 2022; Vanderbosch et al., 2022). They are distributed in seven confirmed types (number of objects), namely ZZ Ceti (or DAV) stars (494), GW Lib stars (18), V777 Her (or DBV) stars (49), hot DAV stars (1), GW Vir stars (24), ELMV stars (12), and pre-ELMV stars (8). There are one additional claimed class of pulsating WDs, the DQV stars. The location of the different kinds of WD and pre-WDs in the $\log T_{\rm eff} - \log g$ is depicted in Fig. 1 (details can be found in Córsico et al., 2019).

3.1. GW Vir variables

The GW Vir variable stars are pulsating PG 1159 stars, after the prototype of the class, PG 1159−035 (McGraw, 1979). This is the hottest known class of pulsating WDs and pre-WDs (80 000 K $\lesssim T_{\rm eff} \lesssim$ 180 000 K and $5.5 \lesssim \log g \lesssim 7.5$), constituted by H-deficient, C-, O- and He-rich atmosphere WD and pre-WD stars. This class includes stars that are still surrounded by a nebula –the variable planetary nebula nuclei, designed as PNNVs– and stars that lack a nebula –called DOVs. The location of the known GW Vir variable stars in the $\log T_{\rm eff} - \log g$ diagram is displayed in Fig. 2. Regarding GW Vir stars, the *Kepler* mission only observed the prototypical star of the class (PG 1159−035; da Rosa et al., 2022). At variance with this, several GW Vir variables were scrutinized by the *TESS* mission, including four new objects discovered with this space telescope.

In a thorough study, Córsico et al. (2021) analyzed exhaustively six already known GW Vir stars using observations collected by the *TESS* mission. They processed and analyzed observations of RX J2117+3412 (TIC 117070953), HS 2324+3944 (TIC 352444061), NGC 6905 (TIC 402913811), NGC 1501 (TIC 084306468), NGC 2371 (TIC 446005482), and K 1−16 (TIC 233689607). A detailed asteroseismological analysis of these stars was carried out on the basis of La Plata Group's* PG 1159 evolutionary models that take into account the complete evolution of the progenitor stars, this being a crucial condition to be able to correctly assess the period spectra of this type of objects. Córsico et al. (2021) extracted 58 periods from the *TESS* light curves of these GW Vir stars using a standard prewhitening procedure to derive the potential pulsation frequencies. All the oscillation frequencies that they found are associated with g-mode pulsations, with periods spanning from $\sim$ 817 s to $\sim$ 2682 s. The authors found a constant period spacings for all but one star (K 1−16), which allowed them to infer the stellar masses and constrain the harmonic degree ℓ of the modes. Based on rotational frequency splittings, they derived the rotation period of RX J2117+3412, obtaining a value in agreement

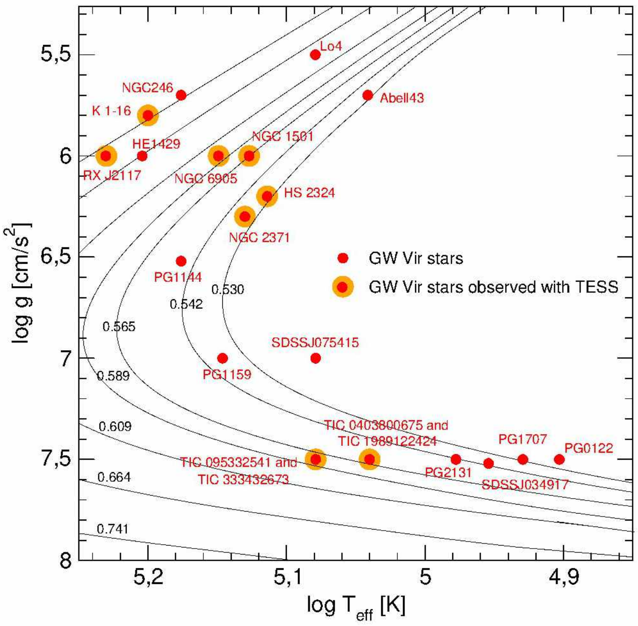

Figure 2: Location of the known GW Vir variable stars in the $\log T_{\rm eff} - \log g$ plane depicted with red circles. Thin solid curves show the post-born again evolutionary tracks from Miller Bertolami & Althaus (2006) for different stellar masses. The location of the GW Vir stars observed with *TESS* are emphasized with large orange circles. In particular, the stars TIC 333432673, TIC 095332541, TIC 0403800675, and TIC 1989122424 have been discovered with *TESS* observations.

with previous determinations. An important point in this study is that to carry out the asteroseismological analyses, the authors combined the periods observed from the ground telescopes with those detected by *TESS*, allowing them to obtain an expanded period spectrum with numerous periods for each analyzed star. They performed period-to-period fit analyses on five of the six analyzed stars. For four stars (RX J2117+3412, HS 2324+3944, NGC 1501, and NGC 2371), they were able to find an asteroseismological model with masses in agreement with the stellar mass values inferred from the period spacings, and are generally compatible with the spectroscopic masses. Employing the seismological models, they derived the seismological distance, and compared it with the precise astrometric distance measured with *Gaia*, finding good agreement in some cases. An interesting finding is that the period spectrum of K 1−16 exhibits dramatic changes in frequency and amplitude, something that made it difficult the analysis. In summary, the findings of Córsico et al. (2021) confirmed the results derived for these stars on the basis of ground-based observations.

Uzundag et al. (2021) reported the discovery of two new GW Vir stars with *TESS* data, TIC 333432673 and TIC 095332541. Both stars are characterized by $T_{\rm eff} = 120\,000 \pm 10\,000$ K, $\log g = 7.5 \pm 0.5$, and $M_\star = 0.58^{+0.16}_{-0.08} M_\odot$, only differing in their surface He/C composition. These authors presented observations from the extended *TESS* mission in both 120 s short-cadence and

*http://evolgroup.fcaglp.unlp.edu.ar/

20 s ultra-short-cadence mode of these two pre-WDs showing H deficiency. Uzundag et al. (2021) applied the tools of asteroseismology with the aim of deriving their structural parameters and seismological distances. The asteroseismological analysis of TIC 333432673 allowed the authors to find a constant period spacing compatible with a stellar mass $M_\star \sim 0.60 - 0.61 M_\odot$, and an asteroseismological model for this star with a stellar mass $M_\star = 0.589 \pm 0.020 M_\odot$, as well as a seismological distance of $d = 459^{+188}_{-156}$ pc. For this star, there is an excellent agreement between the different methods to infer the stellar mass, and also between the seismological distance and that measured with *Gaia* ($d_{\rm Gaia} = 389^{+5.6}_{-5.2}$ pc). For TIC 095332541, there is a possible period spacing that suggests a stellar mass of $M_\star \sim 0.55 - 0.57 M_\odot$. Unfortunately, the authors were not able to find an asteroseismological model for this star.

Finally, Uzundag et al. (2022) announced the discovery of two additional GW Vir stars, TIC 0403800675 (WD J115727.68−280349.64) and TIC 1989122424 (WD J211738.38−552801.18) employing observations collected by *TESS*. These stars are characterized by $T_{\rm eff} = 110\,000 \pm 10\,000$ K, $\log g = 7.5 \pm 0.5$, but different He/C composition. Their *TESS* light curves reveal the presence of oscillations with periods in a narrow range between 400 and 410 s, which are associated with typical g-modes. By performing a fit to their spectral energy distributions, the authors found for both stars radii and luminosities of $R_\star = 0.019 \pm 0.002\, R_\odot$ and $\log(L_\star/L_\odot) = 1.68^{+0.15}_{-0.24}$, respectively. Employing state-of-the-art evolutionary tracks of PG 1159 stars, they found a stellar mass of for both stars of $0.56^{+0.15}_{-0.05} M_\odot$ from the $\log g - T_{\rm eff}$ diagram, and $0.60^{+0.11}_{-0.09} M_\odot$ from the Hertzsprung Russell diagram. Unfortunately, due to the fact that both stars exhibit just only two periods each, it is not possible to perform an asteroseismological modeling, something that will have to wait for more periods to be detected in future observations.

3.2. DBV variables

The DBV or V777 Her variable stars are pulsating DB WDs, characterized by atmospheres almost pure in He, effective temperatures in the range $22\,400$ K $\lesssim T_{\rm eff} \lesssim 32\,000$ K and surface gravities in the interval $7.5 \lesssim \log g \lesssim 8.3$. The location of the known DBV variable stars in the $T_{\rm eff} - \log g$ diagram is shown in Fig. 3.

The first pulsating WD analyzed with *TESS* was the DBV star WD0158−160 (also called EC 01585−1600, G272−B2A, TIC 257459955; Bell et al., 2019). TIC 257459955 is an already known DBV WD with $T_{\rm eff} = 24\,100$ K and $\log g = 7.88$ (Rolland et al., 2018), or alternatively, $T_{\rm eff} = 25\,500$ K and $\log g = 7.94$ (Voss et al., 2007). Bell et al. (2019) found 9 independent periods in the range [245 − 866] sec, suitable for asteroseismology. The period spacing is $\Delta\Pi = 38.1 \pm 1.0$ s, which is associated to $\ell = 1$ g-modes. Its comparison with the average of the computed period spacings provides an estimate of the stellar mass. This procedure points to a stellar mass of $M_\star = 0.621 \pm 0.06 M_\odot$,

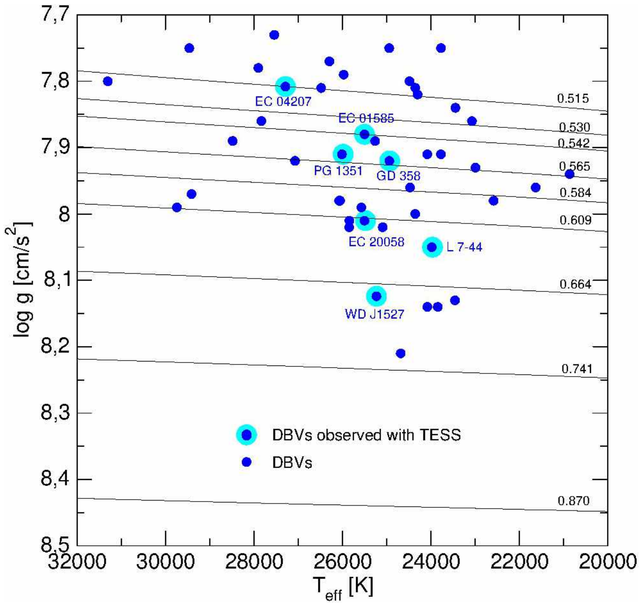

Figure 3: Location of the known DBV WDs on the $T_{\rm eff} - \log g$ diagram, marked with blue circles. Thin solid curves show the DB WD evolutionary tracks from Althaus et al. (2009) for different stellar masses. The location of the DBV stars observed with *TESS* are emphasized with large cyan circles. In particular, the stars L 7−44 and WD J1527 have been discovered with *TESS* observations.

or alternatively, $M_\star = 0.658 \pm 0.10 M_\odot$, according to the two different spectroscopic determinations of $T_{\rm eff}$. They are higher than the spectroscopic estimates ($M_\star = 0.542 - 0.557 M_\odot$). The star also has been analyzed by means of period-to-period fits by employing the fully evolutionary-model approach of the La Plata Group, and also the parametric approach of the Texas Group (Bischoff-Kim & Montgomery, 2018). The solution that satisfies the spectroscopic parameters and the astrometric constraints from *Gaia* is a DB WD model with $M_\star \sim 0.60 M_\odot$, $T_{\rm eff} \sim 25\,600$ K, $M_{\rm He} \sim 3 \times 10^{-2} M_\star$, $d \sim 67$ pc, and a rotation period of ~ 7 or ~ 14 hours.

The second DBV star studied with *TESS* is the prototypical object GD 358 (Córsico et al., 2022b). GD 358 (or V777 Her) has a *TESS* Input Catalog (TIC) number TIC 219074038. It is the brightest ($m_{\rm V} = 13.7$) and most extensively studied DBV star. Its spectroscopic surface parameters are $T_{\rm eff} = 24\,937 \pm 1018$ K and $\log g = 7.92 \pm 0.05$ according to Bédard et al. (2017) from optical data, although the previous analysis by Nitta et al. (2012) and Koester et al. (2014) using optical and UV data gives $T_{\rm eff} = 24\,000 \pm 500$ K and $\log g = 7.8 \pm 0.05$ (Fig.1). Recently, Kong & Luo (2021) derived the atmospheric parameters of GD 358 with *LAMOST* data and found $T_{\rm eff} = 24\,075 \pm 124$ K and $\log g = 7.827 \pm 0.01$ dex. GD 358 has been extensively observed by the *WET* collaboration (Winget et al., 1994; Vuille et al., 2000; Kepler et al., 2003; Provencal et al., 2009). The most recent and thorough analysis of this star has been carried out by Bischoff-Kim et al. (2019), who through an impressive effort collected and reduced data from 34 years of photometric observations, including archival data from 1982 to 2006, and 1195.2 hr of observations from 2007 to 2016. Córsico et al. (2022b) detected 26 periodicities from the *TESS* light curve of this DBV star using a standard pre-whitening. The oscillation frequencies are associated with nonradial g-mode pulsations with periods from ~ 422 s to ~ 1087 s. Moreover, they detected 8 combination frequencies between ~ 543 s and ~ 295 s. The authors combined these data with a huge amount of observations from the ground (Bischoff-Kim et al., 2019) and found a constant period spacing of 39.25 ± 0.17 s, which helped them to infer its mass ($M_\star = 0.588 \pm 0.024 M_\odot$) and constrain the harmonic degree ℓ of the modes. Córsico et al. (2022b) performed a period-fit analysis on GD 358, and were successful in finding an asteroseismological model with a stellar mass $M_\star = 0.584^{+0.025}_{-0.019} M_\odot$, compatible with the stellar mass derived from the period spacing, and in line with the spectroscopic mass ($M_\star = 0.560 \pm 0.028 M_\odot$). In agreement with previous works, they found that the frequency splittings vary according to the radial order of the modes, suggesting differential rotation. Employing the seismological model made it possible to estimate the seismological distance ($d_{\rm seis} = 42.85 \pm 0.73$ pc) of GD 358, which is in excellent agreement with the precise astrometric distance measured by *GAIA* EDR3 ($d_{\rm GAIA} = 43.02 \pm 0.04$ pc). The authors concluded that the high-quality of data measured with *TESS*, used in combination with data taken from ground-based observatories, provides invaluable information for conducting asteroseismological studies of DBV stars, analogously to what happens with other types of pulsating WD stars.

Finally, an ongoing study of DBVs with *TESS* is that of Córsico et al. (2022a), where a detailed asteroseismological analysis of five DBV stars is reported. They processed and analyzed *TESS* observations of the three already known DBV stars PG 1351+489 (TIC 471015205), EC 20058−5234 (TIC 101622737), and EC 04207−4748 (TIC 153708460), and also two new DBV pulsators WD J1527−4502 (TIC 150808542) and WD 1708−871 (TIC 451533898), whose variability is reported for the first time in that paper. Similarly to what was done for the other DBVs, in this analysis it is expected to find the stellar mass of the stars under study through the constant period spacing (when it exists), and through fits of individual periods, which allow to find asteroseismological models. The validity of these asteroseismological models can be checked by calculating the seismological distances and comparing them with the astrometric distances derived by *Gaia*.

3.3. ZZ Ceti variables

The DAV or ZZ Ceti variable stars are pulsating DA WDs, characterized by almost pure-H atmospheres. They are the most numerous pulsating WDs. DAVs are located at low effective temperatures and high gravities ($10\,400$ K $\lesssim T_{\rm eff} \lesssim 12\,400$ K and $7.5 \lesssim \log g \lesssim 9.1$). It was the first class of pulsating WDs to be detected (Landolt, 1968). The location of the known ZZ Ceti variable stars in the $T_{\rm eff} - \log g$ diagram is shown in Fig. 4.

The first study related to DA WDs using *TESS* observations was carried out by Althaus et al. (2020), although not precisely in relation to the already known DAVs, but rather in connection to the possible existence of "warm" pulsating DA WDs, that is, H rich WDs with temperatures larger than those that characterize DAVs. The motivation of Althaus et al. (2020) stems from the pioneering theoretical work of Winget et al. (1982), who predicted the existence of pulsating DA WD stars with $T_{\rm eff} \sim 19\,000$ K. However, to date, no pulsating warm DA WD has been detected. Althaus et al. (2020) re-examined the pulsational predictions for such WDs on the basis of new evolutionary models, and also analyzed a sample of warm DA WDs observed by the *TESS* satellite in order to search for the possible pulsational signals. Althaus et al. (2020) computed WD evolutionary sequences with extremely low H content, appropriate for the study of warm DA WDs, and their non-adiabatic pulsations. They found that extended and smooth He/H transition zones inhibit the excitation of g modes due to partial ionization of He below the H envelope, and only in the case that the H/He transition is assumed to be much more steep, do the models experience pulsational instability. In this case, excited modes are found only in WDs models with H envelopes in the range of $-14.5 \lesssim \log(M_{\rm H}/M_\star) \lesssim -10$ and at effective temperatures higher than those typical of ZZ Ceti stars, in agreement with the previous study by Winget et al. (1982). Althaus et al. (2020) found that none of the warm DAs observed by the *TESS* are pulsating. The study suggests that the non-detection of pulsating warm DA WDs, if WDs with ultra-thin H envelopes do exist, could be attributed to the presence of a smooth and extended H/He transition zone. This could be considered as an indirect proof that element diffusion indeed operates in the interior of WDs.

The second pulsational study of DA WDs carried out with *TESS* observations is that of Bognár et al. (2020). They presented results on 18 previously known ZZ Ceti stars observed in 120 s cadence mode during the survey observation of the southern ecliptic hemisphere. They compared the frequencies detected with *TESS* with findings of previous ground-based observations, and detected possible amplitude or phase variations during the TESS observations in some stars (EC 23487−2424, BPM 30551, and MCT 0145−2211), something that was not previously identified from observations observations from the ground. Interestingly enough, they found that HE 0532−5605 may be a new outbursting ZZ Ceti star (see Bell et al., 2015). On the other hand, they detected more than 40 pulsation frequencies in seven ZZ Ceti stars, but did not detect any significant pulsation frequencies in the Fourier transforms of ten observed objects, due to a combination of their intrinsic faintness and/or crowding on the large *TESS* pixels. In particular, *TESS* observations allowed the detection of new frequencies for five stars (EC 23487−2424, BPM 31594, BPM 30551, MCT 0145−2211, HS 0507+0434B).

The most comprehensive study of ZZ Cetis using *TESS* data up to now is that of Romero et al. (2022). These authors reported the discovery of 74 new ZZ Cetis with the data obtained by *TESS* from Sectors 1 to 39, corresponding to the first 3 years of the mission. This includes objects from the southern hemisphere (Sectors

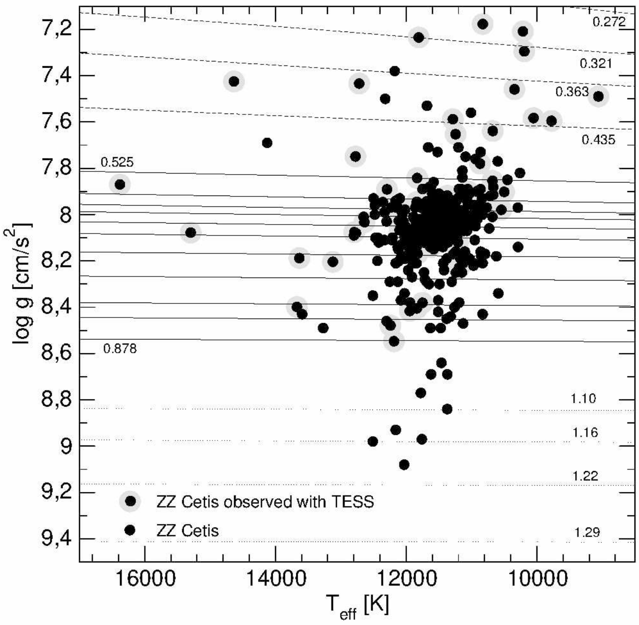

Figure 4: Location of the known ZZ Cetis on the $T_{\rm eff} - \log g$ plane, depicted with black circles. Dashed curves show the low-mass He-core DA WD evolutionary tracks from Althaus et al. (2013), solid curves depict the CO-core DA WD evolutionary tracks from Renedo et al. (2010), and dotted curves display the ultra-massive ONe-core DA WD evolutionary tracks from Camisassa et al. (2019), for different stellar masses. The location of the ZZ Ceti stars observed with *TESS* are emphasized with large gray circles.

1-13 and 27-39) and the northern hemisphere (Sectors 14-26), observed with 120 s and 20 s cadence. The sample of new ZZ Cetis includes 13 low-mass and one ELM WD candidate, considering the mass determinations from fitting *Gaia* magnitudes and parallax. In addition, Romero et al. (2022) present follow-up time series photometry from ground-based telescopes for 11 objects, which allowed them to detect a larger number of periods. For each object, they analyzed the period spectra and performed an asteroseismological analysis, and estimated the structure parameters $(M_\star, T_{\rm eff}, M_{\rm H})$ of the sample. They derived a mean seismological mass of $\langle M_{\rm seis}\rangle = 0.635 \pm 0.015 M_\odot$, in agreement with the mean mass using estimates from *Gaia* data, which is $\langle M_{\rm phot}\rangle = 0.631 \pm 0.040 M_\odot$, and with the mean mass of previously known ZZ Cetis of $\langle M_\star = 0.644 \pm 0.034 M_\odot\rangle$. The new 74 bright ZZ Cetis discovered by these authors increases the number of ZZ Cetis by $\sim 20\%$, leading to 494 the total number of known pulsating WD stars of this class.

3.4. Pre-ELMV and ELMV variables

The ELMV variable stars (Extremely Low-Mass WDs variables) have 7800 K $\lesssim T_{\rm eff} \lesssim$ 10 000 K and $6 \lesssim \log g \lesssim 6.8$, pure H atmospheres, and were discovered by Hermes et al. (2012). The pre-ELMV variable stars (8000 K $\lesssim T_{\rm eff} \lesssim$ 13 000 K and $4 \lesssim \log g \lesssim 5$), the probable precursors of ELMVs, were discovered by Maxted et al. (2013). They have H/He atmospheres. So far, few stars in these two categories of pulsating WD and pre-WD stars have been studied with *TESS*.

Wang et al. (2020) reported the discovery of two new pre-ELMV candidates in the *TESS* eclipsing binaries TIC 149160359 and TIC 416264037. Their lightcurves show a typical feature of EL CVn-type binaries. The less-massive components of the two binaries are both probably thermally bloated, pre-ELMVs. TIC 149160359 was found to pulsate in 21 independent frequencies, 4 of which are between 1139 s and 1359 s, and are associated to pulsation modes of the pre-ELM WD component. The Fourier amplitude spectrum of TIC 416264037 shows two pulsation periods at 706 s and 769 s, likely corresponding to the pre-ELMV component. Low-frequency signals (long periods) are also detected in both TIC 149160359 and TIC 416264037, and are probably due to the intrinsic pulsations of their δ Sct-type primary components.

Using observations made with the *TESS* space telescope, Lopez et al. (2021) discovered pulsations in the ELM WD GD 278. This star was observed by *TESS* in Sector 18 at a 2-min cadence for roughly 24 d. The *TESS* data reveal at least 19 significant periodicities between 2447 − 6729 s, one of which is the longest pulsation period ever detected in a pulsating WD. Previous spectroscopy found that this ELMV star is in a 4.61 hr orbit with an unseen $> 0.4 M_\odot$ companion and has $T_{\rm eff}$ = 9230 ± 100 K and $\log g = 6.627 \pm 0.056$, which corresponds to a mass of $0.191 \pm 0.013 M_\odot$. The star exhibits clear signatures of rotational splittings of frequencies, compatible with a stellar rotation period of roughly 10 hr, making GD 278 the first ELMV with a measured rotation rate. The spectrum of available periods does not allow finding a single asteroseismological model. Asteroseismology reveals two main possible solutions roughly consistent with the spectroscopic parameters of this ELM WD, but with vastly different H-layer masses. To break this degeneracy of solutions it would be useful to employ the stellar parallax, and thus the astrometric distance of the star.

4. Conclusions

The ongoing *TESS* space mission is being very successful in the search for extrasolar planets, but also in the area of asteroseismology for many classes of pulsating stars, in particular, pulsating WDs and pre-WDs.

In this work, we have briefly reviewed the results of 3 articles focused on GW Vir stars, 3 works dedicated to DBVs, 3 studies about ZZ Cetis, and 2 articles focused on pre-ELMVs and ELMVs. All these works involve the discovery of new pulsating WDs and pre-WDs and/or the follow up study of already known pulsating stars with observations from space, for a total of 112 objects.

Admittedly, this is just a partial account of the performance of the *TESS* mission concerning pulsating WDs and pre-WDs, covering only the first 3 years of the mission. Undoubtedly, in the near future there will be numerous discoveries of new pulsating WDs and pre-WDs and additional observations of already known pulsating objects that will help to enlarge the lists of periods available for asteroseismology. Ongoing space missions such as *TESS*, the focus of this article, and *Cheops* (Moya et al., 2018), as well as future missions such as *Plato* (Piotto, 2018), will participate in this enterprise. All this wealth of knowledge will probably help to solve some of the mysteries surrounding these ancient pulsating stars.

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