TESS Asteroseismic Analysis of the Known Exoplanet Host Star HD 222076

Chen Jiang 姜晨1, Timothy R. Bedding2,3, Keivan G. Stassun4,5, Dimitri Veras6,7,27, Enrico Corsaro8,9, Derek L. Buzasi10, Przemyslaw Mikołajczyk10, Qian-sheng Zhang 张钱生11,12,13,14, Jian-wen Ou 欧建文15,16,26, Tiago L. Campante15,16, Thaïse S. Rodrigues17, Benard Nsamba15,18, Diego Bossini15, Jia Mian Joel Ong19, Mutlu Yildız21, Zeynep Çelik Orhan21, Sibel Örtel21, Tao Wu 吴涛22,23,24, Xinyi Zhang 张昕怡22,23,25, Tanda Li 李坦达26, Sarbani Basu20, Margarida S. Cunha15,16,26, Jürgen Christensen-Dalsgaard10, and William J. Chaplin11,26

1 School of Physics and Astronomy, Sun Yat-Sen University, No. 135, Xingang Xi Road, Guangzhou, 510275, People’s Republic of China
2 Sydney Institute for Astronomy, Sun Yat-Sen University, No. 135, Xingang Xi Road, Guangzhou, 510275, People’s Republic of China
3 Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark
4 Vanderbilt University, Department of Physics and Astronomy, 6301 Stevenson Center Ln., Nashville, TN 37235, USA
5 Vanderbilt Initiative in Data-intensive Astrophysics (VIDA), 6301 Stevenson Center Ln., Nashville, TN 37235, USA
6 Centre for Exoplanets and Habitation, University of Warwick, Coventry CV4 7AL, UK
7 Department of Physics, University of Warwick, Coventry CV4 7AL, UK
8 INAF–Osservatorio Astrofisico di Catania, via S. Sofia 78, I-95123 Catania, Italy
9 Department of Chemistry & Physics, Florida Gulf Coast University, 10501 FGCU Boulevard S., Fort Myers, FL 33965, USA
10 Astronomical Institute, University of Porto, Rua das Estrelas, 4150-762 Porto, Portugal
11 Yunnan Observatories, Chinese Academy of Sciences, 396 Yangfangwang, Guandu District, Kunming 650216, People’s Republic of China
12 Center for Astronomical Mega-Science, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, People’s Republic of China
13 Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, 396 Yangfangwang, Guandu District, Kunming 650216, People’s Republic of China
14 University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
15 Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
16 Departamento de Física e Astronomia, Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre, s/n, 4169-007 Porto, Portugal
17 Osservatorio Astronomico di Padova—INAF, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy
18 Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany
19 Department of Earth and Planetary Sciences, University of California, Riverside, CA 92521, USA
20 Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101, USA
21 Osservatorio Astrofisico di Catania, via S. Sofia 78, I-95123 Catania, Italy
22 Yunnan Observatories, Chinese Academy of Sciences, 396 Yangfangwang, Guandu District, Kunming 650216, People’s Republic of China
23 Key Laboratory for Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, 396 Yangfangwang, Guandu District, Kunming 650216, People’s Republic of China
24 Center for Astronomical Mega-Science, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, People’s Republic of China
25 University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
26 School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK

Received 2020 March 8; revised 2020 April 28; accepted 2020 April 29; published 2020 June 15

Abstract

The Transiting Exoplanet Survey Satellite (TESS) is an all-sky survey mission aiming to search for exoplanets that transit bright stars. The high-quality photometric data of TESS are excellent for the asteroseismic study of solar-like stars. In this work, we present an asteroseismic analysis of the red-giant star HD 222076 hosting a long-period (2.4 yr) giant planet discovered through radial velocities. Solar-like oscillations of HD 222076 are detected around 203 µHz by TESS for the first time. Asteroseismic modeling, using global asteroseismic parameters as inputs, yields a determination of the stellar mass \( M_\ast = 1.12 \pm 0.12 \, M_\odot \), radius \( R_\ast = 4.34 \pm 0.21 \, R_\odot \), and age \( 7.4 \pm 2.7 \, \text{Gyr} \), with precisions greatly improved from previous studies. The period spacing of the dipolar mixed modes extracted from the observed power spectrum reveals that the star is on the red-giant branch burning hydrogen in a shell surrounding the core. We find that the planet will not escape the tidal pull of the star and will be engulfed into it within about 800 Myr, before the tip of the red-giant branch is reached.

Unified Astronomy Thesaurus concepts: Asteroseismology (73); Exoplanet systems (484)

1. Introduction

Thanks to the very long duration and high precision of photometric space observation missions, such as CoRoT (Baglin et al. 2006) and Kepler (Borucki et al. 2010), asteroseismology has made major advances in the understanding of stellar interior physics and evolution. In particular, the detection of oscillations in solar-type and red-giant stars has led to breakthroughs such as the discovery of fast core rotation and a way to distinguish between hydrogen-burning stars and stars that are also burning helium in their cores (see Chaplin & Miglio 2013, for a review).

With the development of data analysis techniques (e.g., Corsaro & De Ridder 2014; Corsaro et al. 2015; Davies & Miglio 2016; Lund et al. 2017b) and improved stellar modeling strategies (e.g., Serenelli et al. 2017; Silva Aguirre et al. 2017), as well as optimization procedures that make use of individual oscillation frequencies (Metcalfe et al. 2010; Jiang et al. 2011; Mathur et al. 2012; Silva Aguirre et al. 2015; Rendle et al. 2019), asteroseismology has also proven to be an efficient tool to estimate fundamental stellar properties such as stellar
masses, radii, and ages. This, in turn, enables the systematic characterization of exoplanet host stars through asteroseismology, which provides unmatched precision in the absolute properties of their planets (Ballard et al. 2014; Campante et al. 2015, 2019; Silva Aguirre et al. 2015; Lundkvist et al. 2016; Huber et al. 2019). Furthermore, the synergy between exoplanet research and asteroseismology also enables us to set constraints on the spin–orbit alignment of exoplanet systems (Huber et al. 2013; Benomar et al. 2014; Chaplin et al. 2014a; Lund et al. 2014; Campante et al. 2016a; Kamiaka et al. 2019) and to perform statistical inferences on the orbital eccentricities through asterodensity profiling (Kane et al. 2012; Sliski & Kipping 2014; Van Eylen & Albrecht 2015; Van Eylen et al. 2019).

NASA’s Transiting Exoplanet Survey Satellite (TESS) Mission (Ricker et al. 2014) is performing a near all-sky survey for exoplanets using the transit method in an area 400 times larger than that covered by the Kepler mission, reinforcing the synergy between asteroseismology and exoplanet science. Using its dedicated 2 minute cadence and excellent photometric precision observations, TESS is expected to detect oscillations in thousands of solar-like oscillators (Campante et al. 2016b; Schofield et al. 2019), and simulations predict that at least 100 solar-type and red-giant stars observed by TESS will host transiting or nontransiting exoplanets (Campante et al. 2016b). Considering the geometric transit probability of each system detected by the radial velocity (RV) method and the observational strategy of TESS, Dalba et al. (2019) predicted that TESS would observe transits for ~11 RV-detected planets in its primary mission. However, only three of these detections were expected to be novel, such that the RV-detected planet was not previously known to transit.

In this paper, we present an asteroseismic analysis of the evolved known host HD 222076, which has a long-period planet detected through the RV method. TESS observed solar-like oscillations for HD 222076 for the first time. We use these oscillations in detailed stellar modeling to derive the mass, radius, and age of the host star. Detections of oscillations by TESS in the previously known exoplanet host stars HD 212771 and HD 203949 were reported by Campante et al. (2019), following on the discovery of the first planet transiting a star (TOI-197 or TESS Object of Interest 197) in which oscillations could be measured (Huber et al. 2019).

2. Observations

2.1. High-resolution Spectroscopy

HD 222076 (TIC 325178933 and HIP 116630) is a bright (with apparent TESS magnitude $T = 6.59$), spectroscopically-classified red-giant-branch star (K1 III; Houk & Cowley 1975). It is among the targets of an RV survey of 164 bright G and K giant stars in the Southern Hemisphere conducted by Jones et al. (2011), with the purpose of studying the effect of the host star evolution on the inner structure of planetary systems. And it is also listed in the Stars With ExoplanETs Catalog (SWEET-Cat; Santos et al. 2013; Sousa et al. 2018), which provides stellar atmospheric parameters and masses for the planet-host stars derived assuming local thermodynamic equilibrium and using high-resolution and high signal-to-noise spectra. Based on precise radial velocities obtained with three instruments in two parallel planet-search efforts: the UCLES spectrograph (Diego et al. 1990) on the 3.9 m Anglo-Australian Telescope, the CHIRON spectrograph (Tokovinin et al. 2013) on the 1.5 m telescope at CTIO, and the FEROS spectrograph on the 2.2 m telescope at La Silla (Kaufer et al. 1999), Wittenmyer et al. (2017) reported the detection of a giant planet HD 222076b that has an orbital period of $P = 871 \pm 19$ days with a semimajor axis of $a = 1.83 \pm 0.03$ au, and a minimum mass of $m \sin i = 1.56 \pm 0.11 M_{\text{Jup}}$ (with $i$ being the orbital inclination and $M_{\text{Jup}}$ the mass of Jupiter). A complete list of stellar parameters and relevant literature sources are given in Table 1.

2.2. Broadband Photometry and Gaia Parallax

For an independent, empirical determination of the stellar radius, we analyzed the broadband spectral energy distribution (SED) together with the Gaia parallax, following the procedures described in Stassun & Torres (2016) and

| Parameter | Value | References |
|-----------|-------|------------|
| $T_{\text{eff}}$ (K) | 4806 $\pm$ 100 | (4) |
| $\log g$ (cgs) | 3.18 $\pm$ 0.2 | (5) |
| SED and Gaia DR2 Parallax | | |
| $A_V$ | 0.08 $\pm$ 0.02 | (7) |
| $F_{\text{bol}}$ (erg s$^{-1}$ cm$^{-2}$) | $(3.57 \pm 0.13) \times 10^{-8}$ | (7) |
| $R_*$ (R$_{\odot}$) | 4.38 $\pm$ 0.20 | (7) |
| $M_*$ (M$_{\odot}$) | 1.38 $\pm$ 0.14 | (7) |
| $\rho_*$ (gcc) | 0.023 $\pm$ 0.004 | (7) |
| $L_*$ (L$_{\odot}$) | 9.14 $\pm$ 0.33 | (7) |
| $\pi$ (mas) | 11.024 $\pm$ 0.022$^b$ | (8) |

Notes:

$^a$ Based on extrapolated relations of Torres et al. (2010); should be regarded with caution (see Section 2.2).

$^b$ Adjusted for the systematic offset of Stassun & Torres (2018).

References. (1) Stassun et al. (2018b), (2) van Leeuwen (2007), (3) Houk & Cowley (1975), (4) Wittenmyer et al. (2016), (5) Jones et al. (2011), (6) Sousa et al. (2018), (7) this work, (8) Gaia Collaboration et al. (2018).
Stassun et al. (2017, 2018a). We obtained the $B_V$, $V_T$ magnitudes from Tycho-2, the $BVgrbi$ magnitudes from APASS, the $JHK_s$ magnitudes from the Two Micron All Sky Survey, the W1–W4 magnitudes from the Wide-field Infrared Survey Explorer, the $G$ magnitude from Gaia, and the FUV and NUV fluxes from Galaxy Evolution Explorer. Together, the available photometry spans the full stellar SED over the wavelength range 0.15–22 μm (see Figure 1).

We performed a fit using Kurucz stellar atmosphere models, with the priors on effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$), and metallicity ([Fe/H]) from the spectroscopic parameters listed in Table 1. The remaining free parameter is the extinction ($A_V$), which we limited to the maximum line-of-sight extinction from the Schlegel et al. (1998) dust maps. The resulting fit is very good (Figure 1) with a reduced χ² of 3.5, and a best-fit extinction of $A_V = 0.08 \pm 0.02$. Integrating the (unextincted) model SED gives the bolometric flux at Earth of $F_{\text{bol}} = 3.57 \pm 0.13 \times 10^{-8}$ erg s⁻¹ cm⁻². Taking the $F_{\text{bol}}$ and $T_{\text{eff}}$ together with the Gaia parallax, adjusted by $+0.08$ mas to account for the systematic offset reported by Stassun & Torres (2018), gives the stellar radius as $R_* = 4.38 \pm 0.20 ~R_\odot$.

Combining the bolometric flux with the Gaia DR2 distance allows us to derive a nearly model-independent luminosity, which is a valuable constraint for asteroseismic modeling. Using a Gaia parallax ($\pi$) of 11.024 ± 0.022 mas (adjusted for the 0.082 ± 0.055 mas zero-point offset for nearby stars reported by Stassun & Torres 2018) with the bolometric flux obtained above yielded $L_* = 9.14 \pm 0.33 ~L_\odot$.

In addition, we can estimate the stellar mass ($M_*$) from the eclipsing-binary based empirical relations of Torres et al. (2010), which gives $M_* = 1.38 \pm 0.14 ~M_\odot$. This, together with the empirical radius above, gives the mean stellar density $\rho_* = 0.023 \pm 0.004$ g cm⁻³. However, we note that for log $g < 3.5$ the empirical relations of Torres et al. (2010) are extrapolated; therefore, the inferred stellar mass for the log $g$ of HD 222076 should be regarded with caution.

### 2.3. TESS Photometry

TESS observed HD 222076 in 2 minute cadence during Sector 1 of Cycle 1 for a total of 27.9 days. According to Figure 5(b) of Campante et al. (2016b), with this cadence TESS is predicted to detect solar-like oscillations down to an $I$-band magnitude (used as a proxy for the TESS magnitude) of around 10, for a star with effective temperature of 4900 K and luminosity of 9$L_\odot$. Given its TESS magnitude of 6.59, solar-like oscillations are expected to be detected in the light curve of HD 222076. The light curve was produced using a special version of the photometry pipeline28 (Handberg & Lund 2019) maintained by the TESS Asteroseismic Science Operations Center29 (TASOC; Lund et al. 2017a), which is an extended version of the one adopted in the K2P pipeline (Lund et al. 2015) originally developed to generate light curves for data collected by the K2 Mission. Figure 2(a) shows the raw light curve obtained from the TASOC pipeline. The coverage is nearly continuous with a high duty cycle ~96%, displaying an ~2 day gap that separates the two spacecraft orbits in the observing sector. A 2.5 day period of high jitter is seen toward the end of the sector, corresponding to instrumental variations due to the spacecraft’s angular momentum dumping cycle, which is evident in light curves from Sector 1. The transit of planet HD 222076b is not detected by TESS due to the short observation period. For asteroseismic analysis, the raw light curves are subsequently corrected for systematic effects using the KASOC Filter (Handberg & Lund 2014). The corrected light curve is shown in Figure 2(b).

### 3. Asteroseismic Analysis

#### 3.1. Global Oscillation Parameters

To extract oscillation parameters the corrected light curve was analyzed with several different methods (Kurtz 1985; Jiang et al. 2011; Corsaro & De Ridder 2014; Buzzoni et al. 2015; Corsaro et al. 2015), many of which have been extensively applied on Kepler/K2 data (e.g., Hekker et al. 2011; Verner et al. 2011). The top panel of Figure 3 illustrates the power spectrum of HD 222076 computed based on the corrected light curve. The power spectrum shows a frequency-dependent background signal due to stellar activity, granulation, and faculae that can be modeled by a sum of several Lorentzian-like functions (Harvey 1985; Karoff 2008; Kallinger et al. 2014; Corsaro et al. 2017), and a flat noise. The individual components of the background and the final fit using the method by Jiang et al. (2011) are also shown as dashed blue curves and the solid red curve, respectively, in the top panel of Figure 3. Then the total background was subtracted from the power spectrum, and a close-up of the power excess region is shown in the bottom panel of Figure 3.

Next, global seismic parameters such as the frequency of maximum power ($\nu_{\text{max}}$) and the mean large frequency separation ($\Delta \nu$) were measured based on the analysis of the background-corrected power spectrum. In summary, $\nu_{\text{max}}$ was measured by fitting a Gaussian function to the power excess hump of the smoothed power spectrum (Huber et al. 2009; Hekker et al. 2010; Mathur et al. 2010; Kallinger et al. 2014), as shown in Figure 3. Our analysis yielded $\nu_{\text{max}} = 203.0 \pm 3.6$ μHz. To measure $\Delta \nu$ methods like autocorrelation of the amplitude spectrum (Huber et al. 2009; Mosser & Appourchaux 2009), asymptotic or linear fits to the frequencies of the radial modes (mode degree $l = 0$, mode extraction given in Section 3.2) were used, which gave $\Delta \nu = 15.60 \pm 0.13$ μHz. We note that the results from

---

28 https://github.com/tasoc/

29 https://tasoc.dk/
different groups for the two parameters agree within a few percent. A comparison of global oscillation parameters derived from different methods, including the ones used in our analysis, is given by Hekker et al. (2011). The values of $n_{\text{max}}$ and $n_D$ were averages over all results reported by different methods. And the uncertainties of the two parameters were calculated from the scatter over all results from different methods. Values for the two parameters are listed in Table 1.

3.2. Individual Mode Frequencies

The background-corrected power spectrum in Figure 3 shows a clear signature of solar-like oscillations: a regular series of peaks spaced by a large separation. Given that TESS instrument artifacts are not yet well understood, we restricted our analysis to the frequency range between 150 and 270 $\mu$Hz where we observe peaks well above the noise level. In this region we also see multiple peaks due to dipole mixed modes (Beck et al. 2011; Bedding et al. 2011).

Individual frequencies were extracted from the power spectrum with several independent methods ranging from traditional iterative fitting of sine waves, i.e., prewhitening (e.g., Kjeldsen et al. 2005; Lenz & Breger 2005; Bedding et al. 2007; Jiang et al. 2011), to fitting of Lorentzian mode profiles (e.g., Handberg & Campante 2011; Appourchaux et al. 2012; Mosser et al. 2012; Corsaro & De Ridder 2014; Corsaro et al. 2015; Vrard et al. 2015; Davies & Miglio 2016; Handberg et al. 2017; Roxburgh 2017; Kallinger et al. 2018; Corsaro 2019). Most of the $\ell = 0$ and 2 oscillation modes were successfully identified either based on the frequency ridges in the échelle diagram (Bedding & Kjeldsen 2010) or by using a multimodal approach presented in Corsaro (2019). Very good agreement was achieved from a comparison of the frequencies returned by different methods.

In Figure 4, the grayscale échelle diagram is illustrated for the background-corrected power spectrum. The identified modes (filled symbols) shown in the figure are returned by at least two independent methods with frequency differences smaller than the uncertainties. However, due to the relatively short observation time of TESS, mixed mode patterns are not so clear in the échelle diagram. Therefore, the identification of mixed modes needs further confirmation from comparisons with the model frequencies (see Section 4). The final frequency list of the identified peaks is given in Table 2. The radial modes identified from the power spectrum also allowed us to measure $\Delta\nu$ by performing a linear fit. The resulting value of $\Delta\nu$ contributes the final estimate given in Section 3.1.

4. Modeling

A common way to estimate the fundamental stellar properties is to compare calculated model parameters with the observational constraints that include observed asteroseismic parameters and complementary spectroscopic data. We used a number of independent approaches to model the observed stellar parameters and frequencies, including different stellar evolution codes (ASTEC, MESA; Christensen-Dalsgaard 2008a; Paxton et al. 2011, 2013, 2015), oscillation codes (ADIPLS, GYRE Christensen-Dalsgaard 2008b; Townsend & Teitler 2013), and optimization methods (including AIMS, DIAMONDS, PARAM; Corsaro & De Ridder 2014; Rodrigues et al. 2014; Wu & Li 2016, 2017; Rodrigues et al. 2017; Frandsen et al. 2018; Nsamba et al. 2018; Zhang et al. 2018; Ong & Basu 2019; Rendle et al. 2019; Yıldız et al. 2019). Corrections for the surface effect (Kjeldsen et al. 2008; Ball & Gizon 2017; Viani et al. 2018) were employed by most of the adopted methods. The adopted model inputs included the set of $\{[\text{Fe/H}], T_{\text{eff}}, L_\ast, \Delta\nu, \nu\}$. The atmospheric parameters $\{[\text{Fe/H}]$
and $T_{\text{eff}}$) are adopted from Wittenmyer et al. (2017). To investigate the impacts of different inputs, modelers provided results with and without the use of individual frequencies and the luminosity as observable constraints. The diversity of modeling procedures employed implicitly accounts for the impact of using different stellar models and analysis methodologies on the final estimates. While a detailed comparison of the results from different groups is beyond the scope of this paper, we note extensive comparisons of red-giant models and oscillation frequencies computed with nine widely used stellar evolution codes have recently been performed in the context of Aarhus Red Giants Challenge (Christensen-Dalsgaard et al. 2020; Silva Aguirre et al. 2020a).

Overall, most of the codes were able to find adequate fits to the observable constraints, and the outputs are generally consistent with each other. Most modeling codes were able to provide adequate fits to the observed frequencies. As mentioned before, due to the relative short observational time of TESS, the frequency resolution and the peak heights are not good enough, which degrades the possibility to extract the close and the low-amplitude modes from the relative high-noise-level power spectrum. The detectability of solar-like oscillations is connected with the ratio of total mean mode power due to acoustic oscillations to the total background power across the frequency range occupied by the oscillations. This quantity provides a global measure of the signal-to-noise ratio ($S/N$). With TESS 2 minute cadence data the total $S/N$ is predicted to be 3.1 for HD 222076, which is obtained based on the formulae in Campante et al. (2016b) using the noise floor of 60 ppm hr$^{-1/2}$. By comparing the observed frequencies with those from the best-fitting model (see Figure 5), we were able to identify the modes with corresponding mode degrees and orders that are also given in Table 2. The oscillation peaks identified from the spectrum (top panel of Figure 6) are all with a peak height-to-background ratio larger than 4, exceeding the predicted ratio of 3.1. Our asteroseismic analysis indicates that the TESS photometric performance is better than predicted for the case of HD 222076. This is supported by the recent asteroseismic study of 25 TESS red giants by Silva Aguirre et al. (2020b). Among the extracted modes 12 (10 dipole, 2 quadrupole) are closely spaced mixed modes and 2 are $\ell = 3$ modes. The identified dipolar mixed modes are pressure-mode-like ones that have larger amplitudes and hence are more likely detectable. The asymptotic period spacing of dipolar modes

![Figure 3. Top panel: power spectral density (PSD) of HD 222076 and corresponding global model fit (green dashed curve). The PSD is shown in gray and a heavily smoothed (Gaussian with an FWHM of $\Delta\nu$) version in black. The solid red curve is a fit to the background, consisting of three Harvey-like profiles (blue dashed curves) plus the white noise (yellow dashed line). The Gaussian fit to the oscillation power excess is shown by the blue dotted–dashed curve. Bottom panel: background-corrected PSD in the range of the stellar oscillations.](image-url)
Table 2

| \( \ell \) | \( n \) | \( n_p \) | \( n_g \) | \( \nu \) (\( \mu \)Hz) | \( \sigma_\nu \) (\( \mu \)Hz) |
|---|---|---|---|---|---|
| 0 | 9 | 9 | ... | 161.06 | 0.03 |
| 2 | -102 | 9 | -111 | 174.74 | 0.02 |
| 0 | 10 | 10 | ... | 176.71 | 0.03 |
| 1 | -51 | 10 | -61 | 184.81 | 0.07 |
| 1 | -50 | 10 | -60 | 186.62 | 0.03 |
| 2 | -92 | 10 | -102 | 190.31 | 0.02 |
| 0 | 11 | 11 | ... | 192.32 | 0.01 |
| 3 | -131 | 10 | -141 | 195.64 | 0.02 |
| 1 | -46 | 11 | -57 | 198.11 | 0.02 |
| 1 | -45 | 11 | -56 | 200.29 | 0.01 |
| 1 | -44 | 11 | -55 | 202.34 | 0.03 |
| 2 | -84 | 11 | -95 | 205.36 | 0.02 |
| 2 | -83 | 11 | -94 | 205.92 | 0.03 |
| 0 | 12 | 12 | ... | 207.75 | 0.02 |
| 1 | -40 | 12 | -52 | 215.65 | 0.03 |
| 1 | -39 | 12 | -51 | 217.50 | 0.02 |
| 2 | -76 | 12 | -88 | 221.42 | 0.01 |
| 0 | 13 | 13 | ... | 223.42 | 0.02 |
| 3 | -109 | 12 | -121 | 226.86 | 0.03 |
| 1 | -36 | 13 | -49 | 229.69 | 0.02 |
| 1 | -35 | 13 | -48 | 231.26 | 0.02 |
| 2 | -69 | 13 | -82 | 237.34 | 0.02 |
| 0 | 14 | 14 | ... | 239.21 | 0.03 |
| 1 | -31 | 14 | -45 | 246.95 | 0.03 |

Note. Each mode is labeled according to its mode degree \( \ell \), radial order \( n \), radial order of p- and gravity-mode component \( n_p \) and \( n_g \) from the best-fitting model. \( \nu \) is the mode cyclic frequency and \( \sigma_\nu \) the uncertainty of \( \nu \). Modes presented here are all with a height-to-background ratio larger than 4.

Figure 4. Grayscale échelle diagram of the background-corrected PSD. Identified individual mode frequencies are marked with red circles (\( \ell = 0 \)), blue triangles (\( \ell = 2 \)), green diamonds (\( \ell = 1 \)), and purple squares (\( \ell = 3 \)). This figure was made using the échelle package (Hey & Ball 2020).

Figure 5. Échelle diagram showing observed oscillation frequencies (filled gray symbols) and a representative best-fitting model (open colored symbols) computed by ASTEC and ADIPLS, for \( \ell = 0 \) (circles), \( \ell = 1 \) (diamonds), \( \ell = 2 \) (triangles), and \( \ell = 3 \) (squares) modes. Symbol sizes of observed modes are scaled according to the uncertainties, and those of nonradial theoretical modes are scaled using the inverse inertia as a proxy for mode amplitude (Cunha et al. 2015). Modes with lower inertial and hence larger symbol sizes have relatively higher mode amplitudes. Thick model symbols correspond to modes that are matched to observations. Matched model modes are corrected for the surface effect using the combined correction described by Equation (4) in Ball & Gizon (2017).

from the best-fitting model, defined by the radial position of the base of the convection zone \( r_{bcz} \) as

\[
\Delta \Pi_1 = \frac{2\pi^2}{\sqrt{2}} \left( \int_0^{r_{bcz}} N_{BV} \frac{dr}{r} \right)^{-1},
\]

is \( \Delta \Pi_1 = 87.30 \text{ s} \). The frequency-independent \( \Delta \Pi_1 \) is a good model representation of the period spacing (Wu & Li 2019), usually taken as a constant value, derived from fitting the observed frequencies when the gravity-mode-like mixed modes are dense enough on the power spectrum (Mosser et al. 2014). In our case with only pressure-mode-like mixed modes obtained from observation, we estimate the observed period spacing \( \Delta \Pi_{\text{obs}} \), computed as the average spacing of the observed mixed modes (see the bottom panel of Figure 6), as \( \Delta \Pi_{\text{obs}} \approx 45.70 \pm 10.67 \text{ s} \). The large uncertainty on \( \Delta \Pi_{\text{obs}} \) is due to the relatively small spacings between the high-frequency modes. However, the values of \( \Delta \Pi_{\text{obs}} \) and \( \Delta \nu \) indicate that the star HD 222076 is a hydrogen-shell-burning red-giant star (Bedding et al. 2011; Corsaro et al. 2012) that locates before
Figure 6. Top: power density spectrum showing the position of the extracted oscillation peaks identified as $l = 0$ (red dotted), $l = 1$ (green dashed), $l = 2$ (blue dashed–dotted), and $l = 3$ (violet dashed–dotted–dotted–dotted) modes. Bottom: period spacings $\Delta \ell$, computed using Equation (1), is indicated by the dotted horizontal line. The filled green diamonds show the period spacings between two observed consecutive modes.

the luminosity bump, and the best-fitting model corroborates that.

The consolidated values for $M_\star$, $R_\star$, $\rho_\star$, $\log g$, and age $t$ of HD 222076 from asteroseismic modeling are summarized in Table 1, constraining the corresponding properties to $\sim$10%, $\sim$5%, $\sim$6%, $\sim$2%, and $\sim$37%, respectively. The uncertainties on these stellar parameters were recalculated by adding the median uncertainty for a given parameter in quadrature to the standard deviation of the parameter estimates returned by all methods. This takes account of both random and systematic errors estimated from different methods and has been commonly adopted for Kepler (e.g., Chaplin et al. 2014b). Adding seismic information in the optimization methods adds extra constraints to the best-fit model selection process. This should yield much more precise stellar parameters compared to the empirical eclipsing-binary relation of, e.g., Torres et al. (2010). However, the uncertainties on the parameters estimated from the empiric relation presented in Section 2.2 are comparable with those on the asteroseismic values. This is owing to the relatively large uncertainties returned by several modeling methods as well as possible systematic errors reflecting the use of different codes or techniques. Nevertheless, the precision level of stellar parameters obtained in this study resembles that obtained when analyzing the full length of asteroseismic observations from the nominal Kepler mission. In addition, the stellar mass from the asteroseismic modeling is expected to be more accurate than that from the empirical relation, which is extrapolated for HD 222076 (see Section 2.2). The stellar properties estimated in this section indeed have much smaller uncertainties, but are otherwise consistent with those presented in the planet-discovery paper of Wittenmyer et al. (2017).

5. Planet Characterization

HD 222076b is typical of the population of planets orbiting evolved stars, which are generally beyond 1 au and with masses greater than $1 M_{\text{Jup}}$ (e.g., Lovis & Mayor 2007; Döllinger et al. 2009; Bowler et al. 2010; Jones et al. 2014; Grunblatt et al. 2019). Wittenmyer et al. (2017) computed a lower mass bound of $1.56 \pm 0.11 M_{\text{Jup}}$ and a semimajor axis of $1.83 \pm 0.03$ au for HD 222076b. We revise this estimate by using the asteroseismic stellar mass ($1.12 \pm 0.12 M_\odot$) in Table 1 and the orbital period ($871 \pm 19$ days) and velocity semiamplitude ($31.9 \pm 2.3$ m s$^{-1}$) from Wittenmyer et al. (2017), and obtain $a = 1.85 \pm 0.07$ au and $m \sin i = 1.62 \pm 0.17 M_{\text{Jup}}$. We note that by computing the semimajor axis and the minimum mass from the parameters in Wittenmyer et al. (2017) only, we obtain $1.83 \pm 0.14$ au and $1.56 \pm 0.28 M_{\text{Jup}}$, which are larger than the ($\pm 0.03$ au and $\pm 0.11 M_{\text{Jup}}$) uncertainties that they reported. In this sense, our results reduce the uncertainties with the improved stellar mass.

A semimajor axis of under 2 au suggests that a giant planet is in danger of being engulfed during the giant branch phases of stellar evolution (Mustill & Villaver 2012; Villaver et al. 2014; Madappatt et al. 2016; Gallet et al. 2017; Rao et al. 2018; Sun et al. 2018). Here, we explore this possibility by applying the same procedure as in Campante et al. (2019), which is based on the dynamical tidal formalism of Zahn (1977) that was implemented in Villaver et al. (2014), with the added adiabatic
assumption of stellar mass loss (Veras et al. 2011) and wind velocity and density prescriptions from Veras et al. (2015). We do not consider atmospheric evaporation (Schreiber et al. 2019), or the possibility of another hidden planet in the system or any other dynamical process that may affect the planet’s post-main-sequence evolution (Veras 2016).

We find that the planet is engulfed during the red-giant branch phase and fails to reach the asymptotic giant branch phase. The time at which the engulfment occurs is at about \( i = 8.2 \text{ Gyr} \), or about 800 Myr from now; before the tip of the red-giant branch is reached. This result is insensitive to the choice of planet radius, of which the tidal calculation is a function through the frictional force on the planet (we applied two extreme cases of 1.0 \( R_{\text{tip}} \) and 2.0 \( R_{\text{tip}} \)). The result is, however, sensitive to the planet mass: because the computed value of 1.62 \( M_{\text{tip}} \) is a lower limit, this engulfment time represents an upper limit.

6. Conclusion

The analysis performed in this work demonstrates the strong potential of TESS to characterize exoplanets and their host stars using asteroseismology. We have reanalyzed the HD 222076 planet system, which was discovered by Wittenmyer et al. (2017), based on the 2 minute cadence data from TESS. The observation time (27.9 days) of the star is rather short compared to the long orbital period (871 days) of the planet, and we do not see transit from the data. However, the high-quality photometric observation enables us to perform an asteroseismic analysis of the host star, placing strong constraints on the stellar parameters. From the asteroseismic modeling we obtain a value for the stellar mass of 1.12 \( \pm 0.12 M_{\odot} \), a stellar radius of 4.34 \( \pm 0.21 R_{\odot} \) and an age of 7.4 \( \pm 2.7 \text{ Gyr} \). The asteroseismic analysis further allows the detection of 10 dipole mixed modes from the observed power spectrum. The observed period spacing of these mixed modes and the mean large frequency separation reveal that the star HD 222076 is a hydrogen-shell-burning red-giant branch star. Thanks to the measurement of the mixed modes, the evolutionary stage of this star can be analyzed in such a level of detail for the first time.

The updated stellar parameters from our asteroseismic analysis have enabled improved estimations for the lower bound of the planetary mass of \( m \sin i = 1.62 \pm 0.17 M_{\text{tip}} \) and a semimajor axis of \( a = 1.85 \pm 0.07 \text{ au} \). With the value obtained for the semimajor axis, we predict that the giant planet is in danger of being engulfed during the giant branch phase of stellar evolution. Based on the estimated stellar age, the engulfment will occur in about 800 Myr from now, at the latest.

Our asteroseismic analysis indicates that the TESS photometric performance is better than that predicted by Campante et al. (2016b) for the case of HD 222076. Indeed, Silva Aguirre et al. (2020b) found that the quality of TESS photometry is similar to that of Kepler and K2. This emphasizes the potential of TESS for characterizing host stars and understanding their planets.

The project leading to this publication has received funding from the Strategic Priority Research Program of the Chinese Academy of Sciences (grant No. XDB 41000000) and the National Key Program for Science and Technology Research and Development (2017YFB0203300). This paper includes data collected by the TESS mission. Funding for the TESS mission is provided by the NASA Explorer Program. Funding for the TESS Asteroseismic Science Operations Center at Aarhus University is provided by ESA PRODEX (PEA 4000119301) and Stellar Astrophysics Centre (SAC), funded by the Danish National Research Foundation (grant agreement No. DNRF106). J.C. is funded by the Fundamental Research Funds for the Central Universities (grant 116py278) and gratefully thanks Biwei Jiang for the discussions on this work.

Q.-S.Z. is cosponsored by the National Natural Science Foundation of China (grant No. 11303087) and the Ten Thousand Talents Program of Yunnan Province, and foundations of the Chinese Academy of Sciences (Light of West China Program, Youth Innovation Promotion Association).

D.V. gratefully acknowledges the support of the STFC via an Ernest Rutherford Fellowship (grant ST/P003850/1). T.W. and X.-Y.Z. are thankful for the support from the NSFC of China (grant Nos. 11503076, 11773064, 11873084, and 11521303), from Yunnan Applied Basic Research Projects (grant No. 2017B008) and from Youth Innovation Promotion Association of Chinese Academy of Sciences. T.W. and X.-Y. Z. also gratefully acknowledge the computing time granted by the Yunnan Observatories, and provided on the facilities at the Yunnan Observatories Supercomputing Platform. D.L.B. acknowledges support from the Whitaker Center for STEM Education at Florida Gulf Coast University. B.N. acknowledges postdoctoral funding from the Alexander von Humboldt Foundation taken at the Max-Planck-Institut für Astrophysik (MPA). T.D.L. acknowledges support from the Australian Research Council (grant DE180101104), and the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (CartographY GA. 804752). P.M. acknowledges support from NCN grant No. 2016/21/B/ST9/01126. M.Y., Z.C.O., and S.O. acknowledge the Scientific and Technological Research Council of Turkey (TÜBITAK:118F352). T.L.C. acknowledges support from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 792848 (PULSATION). M.S.C. is supported by national funds through FCT—Fundação para a Ciência e a Tecnologia—in the form of a work contract and through the research grants UIDB/04434/2020, UIDP/04434/2020 and PTDC/FIS-AST/30389/2017, and by FEDER—Fundo Europeu de Desenvolvimento Regional through COMPETE2020—Programa Operacional Competitividade e Internacionalização (grant: POCI-01-0145-FEDER-030389).

Facilities: TESS, Gaia, Kepler(K2).

Software: TASOC photometry pipeline (https://github.com/tasoc; Handberg & Lund 2019), DIAMONDS (https://github.com/EnricoCorsaro/DIAMONDS; Corsaro & De Ridder 2014).

ORCID iDs

Chen Jiang (姜晨) https://orcid.org/0000-0002-7614-1665
Timothy R. Bedding https://orcid.org/0000-0001-5222-4661
Keivan G. Stassun https://orcid.org/0000-0002-3481-9052
Dimitri Veras https://orcid.org/0000-0001-8014-6162
Enrico Corsaro https://orcid.org/0000-0001-8835-2075
Derek L. Buzasi https://orcid.org/0000-0002-1988-143X
Przemysław Molkołajczyk https://orcid.org/0000-0001-8916-8050
Qian-sheng Zhang (张钱生) https://orcid.org/0000-0003-2449-6226
