Proposal for *TESS* GI Program

Cycle 7

Cover Page

Title: ASTEROSEISMOLOGY OF BRIGHT SOLAR-TYPE STARS

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Proposal Type: 1-Investigations Using Only Postage Stamp Data (20-Second and/or 2-Minute Cadence Observations)

Subject Category: 2-Stellar Astrophysics

Joint Fermi Proposal? No

Target List: upload

Joint Swift Proposal? No

Number of Targets: 0

ToO Proposal? No

Joint NICER Proposal? No

Effort Level: SMALL

Abstract:
Solar-type stars -- stars with temperatures, radii, and metallicities similar to the Sun -- play a critical role for stellar astrophysics and exoplanet science. Asteroseismology provides a powerful tool to determine fundamental properties such as mass and age, but due to the small amplitudes and fast timescales of the oscillations in solar-type stars only a small number of detections have been made using space-based photometry. Here we propose to use the unique 20-second cadence capabilities from TESS to establish an all-sky benchmark sample of bright asteroseismic solar-type stars, which will enable us to: (i) investigate the connection between magnetic activity cycles and stellar age in solar-type stars and (ii) characterize the fundamental properties of exoplanet host stars.

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General Form

Title: ASTEROSEISMOLOGY OF BRIGHT SOLAR-TYPE STARS

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ASTEROSEISMOLOGY OF BRIGHT SOLAR-TYPE STARS

1 Introduction

Solar-type stars—stars with properties similar to the Sun [1]—play a critical role in stellar astrophysics and exoplanet science. For example, stellar models are anchored on stars similar to our Sun, and understanding magnetic activity cycles for solar-type stars is essential to determine whether or not the magnetic cycle of our Sun is typical [2]. Solar-type stars are also a focal point in exoplanet science, providing prime candidates for direct imaging of exoplanets using next-generation facilities such as the Roman Space Telescope and the Astro2020 flagship mission, and providing targets for high-precision abundance analyses that may be linked to terrestrial planet formation [3].

A powerful method to probe solar-type stars is *asteroseismology*, the study of stellar oscillations. The detection of oscillations enables the precise determination of fundamental properties such as masses and ages, which are poorly constrained through spectroscopy and Gaia alone. However, due to their small amplitudes and fast timescales ($\sim$ minutes), the detection of oscillations in bright solar-type stars with well-measured activity cycles is difficult, and only a handful of targets currently have high S/N detections from space-based photometry. **Here we propose to leverage the unique capabilities of the TESS 20-second data in Cycle 7 to detect oscillations in hundreds of solar-type stars, many of which were recently selected as precursor science targets for the upcoming NASA flagship mission, the Habitable Worlds Observatory.**

2 Scientific Justification

Short-cadence observations by Kepler (1-minute sampling) have yielded oscillations in more than 500 solar-type stars, a sample that has now become an invaluable resource for stellar astrophysics [4]. However, these targets are faint and distant (**Fig. 1**), which limits the availability of: (1) independent constraints on fundamental properties that are required to break parameter degeneracies when modeling the oscillation frequencies [5], and (2) archival observations that can probe long-term magnetic activity cycles. Both of these obstacles can be overcome for bright stars, which have strong constraints such as highly precise parallaxes, archival high-resolution spectra, and long-baseline interferometry, providing nearly-model-independent stellar radii and temperatures [6]. Furthermore, the Kepler and K2 missions were restricted to specific regions of the sky, hindering an all-sky benchmark sample from asteroseismology which can now be established with TESS.

The small size of the current sample of asteroseismic solar analogs seriously limits our ability to answer key questions in stellar astrophysics and exoplanet science. For example, the discovery that old solar-type stars observed by Kepler rotate faster than expected has caused a controversy about the applicability of gyrochronology for stars more evolved than the Sun [7]. The initial sample included $\sim$20 stars and only a handful of these had constraints on their magnetic activity cycles, which are essential to understand the relations between rotation, age, and activity [8]. Similarly, the current sample of exoplanet hosts with asteroseismic data, which enable the precise characterization of exoplanets, is small and heavily biased towards evolved stars that are unlike our Sun [9].

Here, we propose 20-second cadence observations to establish a benchmark sample of asteroseismic solar-type stars. **TESS data from the first extended mission have demonstrated the extraordinary promise of 20-second cadence data for asteroseismology of solar-type stars (Fig. 2).** Specifically, 20-second data show higher photometric precision than 2-minute cadence data for bright stars (Fig. 2, left) [10] and do not suffer from amplitude attenuation caused by the slower 2-minute cadence sampling. These advantages have allowed high S/N detections in some solar-type stars which were serendipitously observed in Cycle 3 (Fig. 2, right). **Cycle 7 provides an opportunity to extend light curve baselines for many bright, nearby solar-type stars, dramatically increasing the potential sample of stars with asteroseismology.**

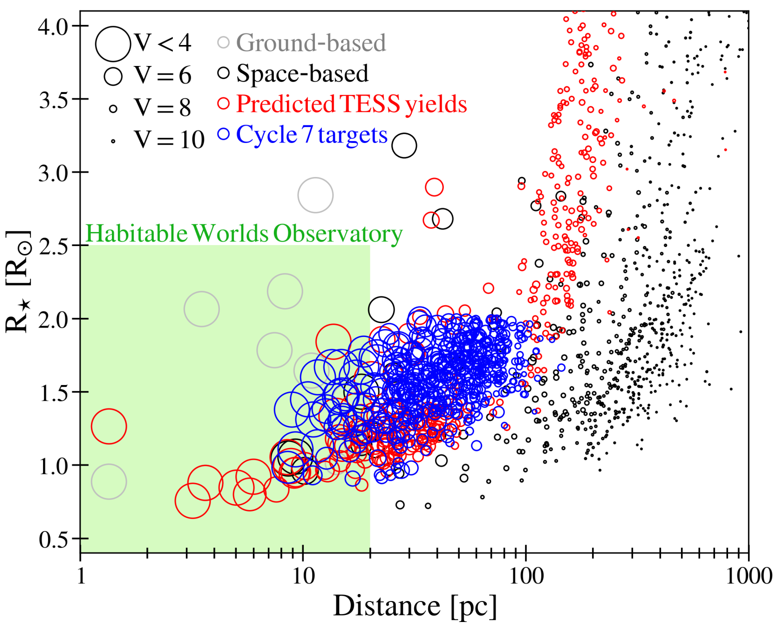

Figure 1: Our program will enable the systematic application of asteroseismology to bright, nearby solar-type stars. Stellar radius versus distance for solar-like oscillators detected by ground-based facilities (gray), Kepler (black), and the expected yield from the TESS prime mission using 2-minute data (red) and from this program using 20-second data in Cycle 7 (blue). Symbol sizes scale with apparent magnitude, and the green rectangle highlights the parameter space from which stars will be selected for the Habitable Worlds Observatory to directly image Earth-like planets.

3 Research Plan

3.1 Target Selection

We selected targets from the recently updated Asteroseismic Target List [ATL, 11] based on the probability of detecting oscillations with TESS. Detection probabilities are calculated from Gaia-derived stellar properties, using the detection recipe developed for Kepler/K2 [12] adapted to the noise properties of TESS. We selected stars by requiring that the frequency of maximum power ($\nu_{\rm max}$) exceeds 1000 μHz, corresponding to main-sequence stars and excluding subgiants ($R \gtrsim 2\,R_{\odot}$). Sampling at 2-minute cadence would cause attenuation of the oscillation amplitudes from proximity to the 2-minute cadence Nyquist frequency ($\sim$4000 μHz), thus requiring 20-second data to enable high S/N detections. For example, oscillations in the bright ($V = 5.0$) solar analog α Mensae A using 2-minute data in the prime mission are attenuated by $\sim$50% in power, severely decreasing the S/N [13]. Similar attenuation for fainter targets will inhibit the detection of oscillations, and thus 20-second cadence is critical for our science goals. Our list was supplemented with a small number of targets that were missing from the ATL, such as stars with known long-term activity cycles from archival data at Mount Wilson, Lowell, and Keck observatories. The final target list includes 1310 targets, with an average of $\sim$200 targets per sector ($\sim$10% of the total 20-second cadence GI allocation). All targets are priority ranked based on the calculated detection probability.

3.2 Asteroseismic Analysis & Follow-Up Observations

We will use publicly available SPOC light curves, which have yielded high S/N detections (Fig. 2, right), and custom light curves to confirm all detections. We will apply open source asteroseismic pipelines to measure oscillation properties, including the frequency of maximum power ($\nu_{\rm max}$), the large frequency separation ($\Delta\nu$), frequencies and amplitudes. Modeling will be performed by combining $\nu_{\rm max}$, $\Delta\nu$ and frequencies with Gaia parallaxes, spectroscopy and interferometry when available. For each star, modeling will yield fundamental properties such as density, radius, mass, surface gravity and age. For a smaller number of stars with the highest S/N, we expect to be able to place constraints on input physics such as the convective mixing length parameter. A large fraction of bright stars on our list have archival high-resolution spectra. For targets of particular interest (e.g. exoplanet hosts) we will obtain additional spectroscopic follow-up observations as needed.

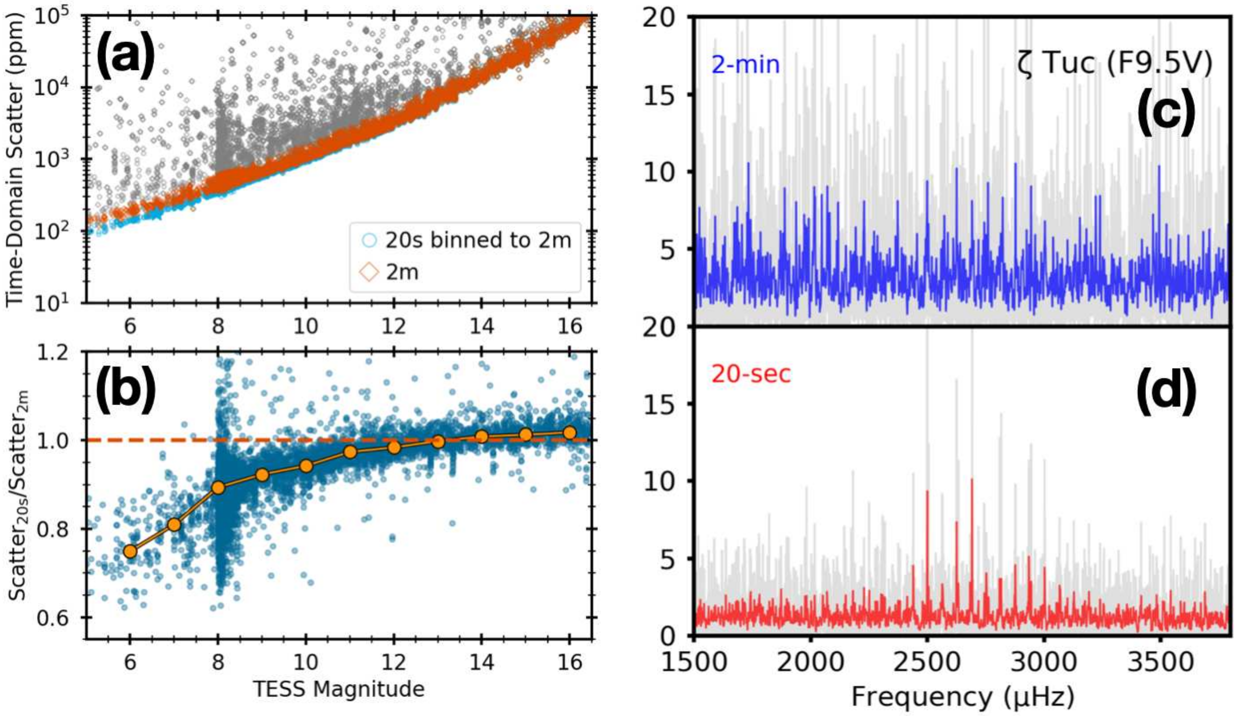

Figure 2: TESS 20-second data have demonstrated extraordinary promise to study bright solar-type stars using asteroseismology. (a) Light curve scatter as a function of TESS magnitude for stars observed in 20-second cadence binned to 2-minute cadence (blue circles) and original 2-minute data (red diamonds). (b) Ratio of the samples in panel (a). (c) Smoothed power spectrum (blue) of ζ Tuc using 2-minute data. (d) Same as (c) but using 20-second data (red).

4 Technical Feasibility

Detectability of Oscillations: Data from the first extended mission have unambiguously confirmed that TESS can detect oscillations in solar analogs (e.g. ζ Tuc, Fig. 2, right). Even with a single sector the extraction of individual frequencies is possible in many cases, and the analysis of detections in currently available TESS data has yielded uncertainties of just ~ 0.01 dex in $\log g$, $\sim 2\%$ in radius, $\sim 5\%$ in mass, $\sim 1\%$ in mean density, and $\lesssim 20\%$ in age [10]. Importantly, these numbers include systematic errors from different model grids, which are frequently neglected. For comparison, uncertainties without asteroseismic constraints are typically worse by at least a factor of ~ 3 [14].
Expected Yield: We performed Monte-Carlo simulations taking into account detection probabilities for individual targets, considering both currently available and forthcoming TESS data. The resulting yield of more than 500 detections in our sample will approximately double the number of stars $\lesssim 1.25\,R_\odot$ with detected oscillations, and provide an all-sky benchmark sample of *nearby* solar-type stars with oscillations detected from space-based photometry (**Fig. 1**).

5 Expected Impact

5.1 Key Science Questions

What is the relation between stellar magnetic activity and age for solar-type stars? Magnetic activity cycles are one of the most intriguing and poorly understood aspects of stellar evolution, but play an important role in validating other age indicators such as the spin-down of stars with time (gyrochronology). An essential ingredient for understanding the interplay between rotation, age, and activity are stars with precise asteroseismic ages for which magnetic activity cycles have been

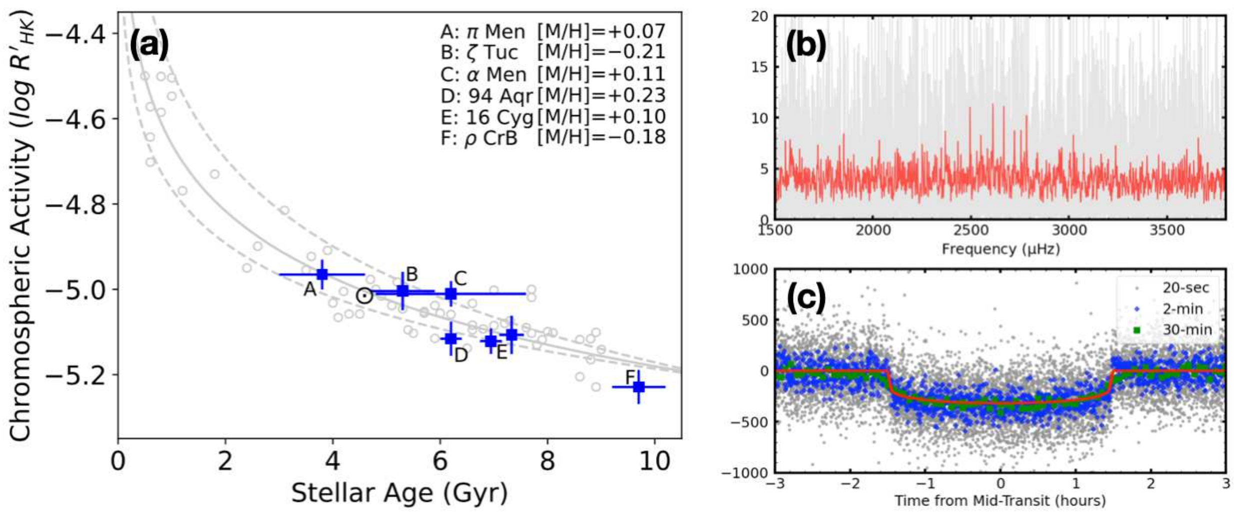

Figure 3: Our program will enable the systematic characterization of magnetic activity and exoplanets for solar-type stars. Left: (a) Chromospheric activity versus age for solar twins (gray) and bright solar-type stars with asteroseismology (blue), showing evidence that stars with the same age but different masses (e.g. α Men and 94 Aqr) have different activity levels. Right: From 20-second data, (b) Power spectrum of π Men and (c) transits of the super-Earth π Men c.

measured from spectroscopy—requiring decades-long archival measurements which are typically only available for bright solar-type stars through long-term programs such as the Mount Wilson, Lowell, and Keck surveys. TESS data have already demonstrated this powerful synergy for a few solar-type stars, hinting that the spread in the activity–age relation is linked to stellar mass and thus the depth of the surface convection zone (Fig. 3a). **Our program will yield precise and accurate asteroseismic ages for additional stars with archival stellar activity constraints, providing an unprecedented data set to calibrate activity–age relations.**

What are the properties of exoplanets orbiting asteroseismic host stars? Asteroseismology is a powerful method to precisely determine radii, masses and ages of exoplanets through the characterization of host stars. In particular, asteroseismic mean stellar densities combined with high-cadence photometry enable precise measurements of eccentricities of small planets [15], constraining formation theories such as planet-planet scattering (predicting non-zero eccentricities) or in-situ formation/disc migration (predicting circular orbits). Furthermore, nearby solar-type stars will be prime candidates for directly imaging exoplanets in reflected light with the Roman Space Telescope and the Habitable Worlds Observatory, which will require precise ages to interpret the possible detection of biosignatures. The use of 20-second data has already enabled the detection of oscillations in π Men (Fig. 3, right), providing precise constraints on the eccentricity of π Men c and its connection to orbital misalignments in the system [16, 17], as well as α Men A, a G7V star at 10 pc that will be a prime target for future exoplanet direct imaging campaigns [13]. **Our program includes 78 known exoplanet hosts and several well-characterized nearby Sun-like stars such as η Cas (F9V, 6 pc), ι Per (G0V, 10 pc), and υ And (F9V, 13 pc).**

6 Work Plan

The PI and Co-I 1 will prioritize targets for data analysis and coordinate the asteroseismic modeling for significant detections. Co-I's 1–5 will contribute to the data analysis while the PI and Co-I's 6–8 will perform asteroseismic modeling. Co-I's 1 and 8 will coordinate spectroscopic follow-up as needed. The PI will be responsible for interpretation, publication, and presentation of results.

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OPEN SCIENCE & DATA MANAGEMENT PLAN (OSDMP)

Data Management Plan

The proposed project, through coordination and collaboration with the TESS Asteroseismic Science Operations Center (TASOC), will generate TESS ultra-short-cadence light curves that are optimized for asteroseismology (<1 MB per target), as well as power density spectra (<2 MB per target) for the analysis of solar-like oscillations. These data products will be archived as fits and txt files in the TASOC database (tasoc.dk) and as High-Level Science Products on MAST by the end of the period of performance. The project may also produce ground-based data products (e.g. high-resolution stellar spectra in fits format) that will be accessible through the existing public data archives of the associated observatories after a 12 month proprietary period. Each data archive has minimal requirements for acknowledgment of the observatory and instrument in any resulting publication. The PI and Co-I 1 will be responsible for implementation of the data sharing plan.

Software Management

The team will make use of existing open source software to reduce, analyze, and interpret the data produced by this investigation. This software is currently available on Github under permissive licenses. No software development is anticipated for this effort. If new software is created, it will be made publicly available to the extent legally permitted per the Scientific Information Policy for the Science Mission Directorate. The PI and Co-I 1 will be responsible for software management.

Open Science Plan

The project will publish all results in peer-reviewed AAS journals, which have been completely open access since 2022. In addition, preprints will be made freely available on arXiv in advance of publication. Additional data derived from the products described above will include global oscillation properties, individual oscillation frequencies and mode identifications, as well as spectroscopic parameters and mean chromospheric activity levels compiled from the literature. These quantities will be archived in the resulting publications using "Data behind the Figure" and "Machine-readable Tables" supplements. The PI and Co-I 1 will be responsible for ensuring open access publication.

TEAM EXPERTISE AND RESOURCES

Travis Metcalfe (PI, White Dwarf Research Corporation)
Daniel Huber (Co-I 1, University of Hawaii)
William Chaplin (Co-I 2, University of Birmingham, UK)
Derek Buzasi (Co-I 3, Florida Gulf Coast University)
Ashley Chontos (Co-I 4, Princeton University)
Hans Kjeldsen (Co-I 5, Aarhus University, Denmark)
Sarbani Basu (Co-I 6, Yale University)
Joergen Christensen-Dalsgaard (Co-I 7, Aarhus University, Denmark)
Marc Pinsonneault (Co-I 8, Ohio State University)

PI Metcalfe is an expert in asteroseismic modeling and will provide overall coordination of the project. Co-I Huber is an expert in asteroseismic data analysis. Co-I Huber and Co-I Pinsonneault will coordinate ground-based spectroscopic follow-up observations through institutional access to telescopes at the University of Hawaii, and Ohio State University. Co-I Chaplin is co-chair of the working group on solar-like oscillators within the TESS Asteroseismic Science Consortium (TASC) and has extensive experience with asteroseismic data analysis. He will also contribute to the coordination of the project within TASC. Co-I Buzasi contributes to the light curve production efforts within TASC from TESS full-frame images as co-chair of the TESS Data for Asteroseismology (T'DA) working group within TASC. He will contribute independent light curves for the asteroseismic analysis, which will be used to confirm the asteroseismic detections from the default SPOC light curves provided by MAST. Co-I's Huber, Chontos, and Kjeldsen are experts in asteroseismic data analysis, including the validation of detections of oscillations, measurements of global asteroseismic parameters and individual frequencies. The PI and Co-I's Basu, Christensen-Dalsgaard, and Pinsonneault are experts in stellar modeling, with access to independent codes and techniques to derive fundamental parameters from asteroseismic observables. These independent results will be used to derive robust systematic errors on derived properties.