Project Summary

Understanding the evolution of stars and their planetary systems requires a reliable method of determining their precise ages and masses. In young stars, both rotation and magnetic activity are empirically correlated with the stellar age. Beyond the middle of their main-sequence lifetimes, this correlation appears to break down for rotation, but it persists for magnetic activity. We propose to recalibrate the empirical activity-age relation, by combining published chromospheric activity measurements of bright stars with asteroseismic ages and masses derived from data obtained by the Transiting Exoplanet Survey Satellite (TESS).

Our target list is drawn from hundreds of bright stars with published multi-year data on chromospheric activity from the Mount Wilson and Lowell surveys, the California Planet Search, as well as smaller samples from other surveys. Asteroseismic analysis relies on short-cadence (2-minute or 20-second) observations, for which target pixel files and light curves have been delivered by the Science Processing and Operations Center (SPOC). Light curves optimized for asteroseismology are available through the TESS Asteroseismic Science Operations Center (TASOC). From a power spectrum of these short-cadence light curves, we will determine the global oscillation properties and/or individual mode frequencies for each of our targets. Asteroseismic radii, masses and ages will be derived from grid-based and detailed modeling, using the observational inputs obtained from TESS data along with spectroscopic constraints gathered from the literature and luminosities from *Gaia* EDR3.

The proposed work will establish a new tool to determine reliable ages for older stars and their planetary systems, where methods based on rotation begin to break down. Spot modulations in older stars are notoriously difficult to detect, both because active regions become smaller and rotation periods grow longer. By contrast, spectroscopic signatures of magnetic activity become weaker but more constant in time, so a single measurement is more likely to be representative of the mean activity level. Such measurements are a natural byproduct of radial velocity follow-up programs, and our new tool will allow these same data to yield the age for fainter targets where asteroseismology is not feasible.

Contents

1 Significance & Objectives

Stellar ages are fundamental to any effort to study the evolution of stars and their planetary systems, but reliable constraints have historically been difficult to obtain. Clusters of stars share a common age, so stellar isochrones can be used to model the properties of the ensemble and determine a precise age for the system. The zero-point of the age scale may vary from one set of isochrones to the next, but a uniform application to the available data sets can at least establish their relative chronology. Isochrone fitting is potentially even more powerful in the era of *Gaia* [1], where questions of cluster membership and the luminosity scale can be established more precisely. However, very few of the currently known planetary systems are in clusters, so a reliable method of determining the ages of field stars is needed.

Asteroseismology employs the same stellar evolution models that are used for isochrone fitting, to measure the properties of an individual star by matching its normal modes of oscillation. In principle, the stellar age and mass are determined from a comparison with the properties of stellar models just like isochrone fitting, but substituting many observational constraints for a single star instead of a few such constraints for many stars. It has been shown that stellar ages are improved substantially when any asteroseismic constraints are available, pushing the 50–100% uncertainties from traditional isochrone fitting down to 10–20% when global oscillation properties or individual mode frequencies are included [2]. The primary difficulty for asteroseismology is that it can only be applied to brighter stars.

Reliable ages for a broader sample of stars and their planetary systems can be obtained if asteroseismic ages are used to calibrate empirical relations with stellar rotation or magnetic activity. After the suggestion that stellar rotation rates and magnetic activity levels diminish together over time [3], the idea of using one or both properties to determine the ages of stars has gradually taken hold. The idea was made more quantitative by establishing the mass-dependence and calibrating a rotation-age relation using young clusters and the Sun [4, 5]. In the absence of additional observations, it was natural to extrapolate these relations to stars beyond the middle of their main-sequence lifetimes. However, over the past few years evidence has emerged that something unexpected occurs in the evolution of stellar rotation around middle-age, limiting the utility of *gyrochronology* relations for older stars [6, 7, 8].

Fortunately, recent observations of chromospheric activity in a large sample of spectroscopic solar twins suggest that, unlike rotation, the evolution of magnetic activity appears to be continuous across this transition (see **Figure 1**). Although the ages adopted for this analysis were derived from isochrones [9], NASA's Transiting Exoplanet Survey Satellite [TESS; 10] can now provide reliable asteroseismic ages for bright stars down to V$\sim$7 all around the sky [11]. When combined with published archives of chromospheric activity levels, **asteroseismic ages can be used to recalibrate the empirical activity-age relation for solar-type stars, which is the main thrust of this proposal.**

Stars are born with a range of initial rotation rates and magnetic field strengths, and beyond the saturated regime the two properties are intricately linked for as long as a global dynamo continues to operate. The large-scale magnetic field gradually slows the rotation over time [12, 13]. Through a process known as magnetic braking, charged particles in the stellar wind follow the magnetic field lines out to the Alfvén radius, shedding angular momentum in the process. In turn, non-uniform rotation modifies the morphology of the magnetic field [14]. Solar-like differential rotation, with a faster equator and slower poles,

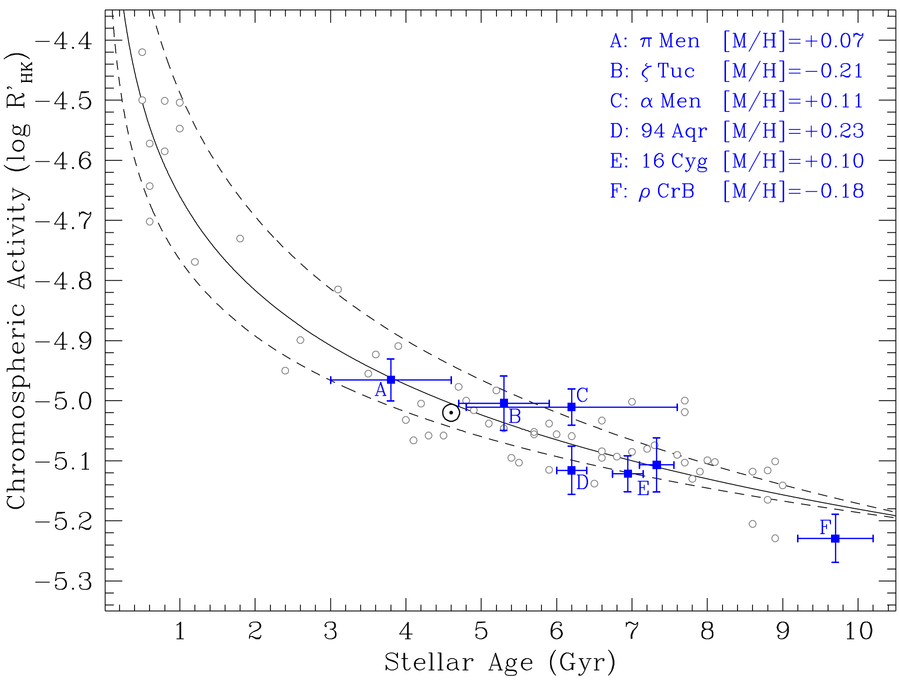

Figure 1: *Activity-age relation for spectroscopic solar twins (gray points) along with several asteroseismic targets from Kepler and TESS (blue points). A fit is shown as a solid line, with the uncertainty range indicated by dotted lines [9]. Additional asteroseismic measurements from TESS will help calibrate the empirical activity-age relation over a range of masses.*

is a natural consequence of convection in the presence of substantial Coriolis forces [15]. The resulting shear wraps up the large-scale poloidal field into a toroidal configuration that ultimately leads to the emergence of active regions on the surface. Through these basic physical processes, stellar rotation and magnetism diminish together over time, each feeding off the other. The mutual feedback can continue as long as rotation and magnetism are coupled through a global dynamo.

This consensus view of magnetic stellar evolution has prevailed for nearly half a century, while both the theoretical foundations and the constraints from young clusters have improved steadily over time [16]. As mentioned briefly above, there is now a more quantitative formulation of the rotation-age relation [4]. Given only the B−V color and rotation period ($P_{\rm rot}$) of a star, gyrochronology yields an empirical stellar age with a precision of 15–20%. This formulation was later revised to account for varying initial conditions (P_0, important in young clusters), and to map the mass-dependence onto a convective overturn time (τ_c) derived from stellar models [5, 17]. This approach more faithfully reproduced the distribution of rotation periods in young clusters, while yielding ages compatible with the earlier formulation for more evolved stars [4]. However, the Sun remained the oldest calibrator, so this empirical relation was untested beyond stellar middle-age.

Observations from the *Kepler* mission provided the first tests of gyrochronology for older clusters and for field stars beyond the age of the Sun. There was good agreement with expectations for the 1 Gyr cluster NGC 6811 [18], and the success was extended to 2.5 Gyr with observations of the cluster NGC 6819 [19]. The first indications of unexpected behavior revealed that no single gyrochronology relation could simultaneously explain the cluster data and the asteroseismic ages for old *Kepler* field stars with measured rotation periods [20]. Anomalously fast rotation among the best characterized *Kepler* asteroseismic targets was subsequently confirmed, and a model was proposed to explain the observations with significantly weakened magnetic braking beyond the middle of a star's main-sequence lifetime [6]. The magnetic counterpart of this rotational transition was identified in chromospheric activity measurements of the *Kepler* targets, showing empirically that the activity level continues to decrease while the rotation rate remains almost constant [21]. It was suggested that the transition might be triggered by a change in the character of differential rotation that was expected from global convection simulations [22, 23]. A coincident shift in stellar dynamo properties was later identified, with the cycle period growing longer and the amplitude becoming smaller at nearly constant rotation [24].

These developments suggest a revised picture of the late stages of magnetic stellar evolution, in which the disruption of differential rotation in the absence of substantial Coriolis forces leads to a gradual decrease in the production of large-scale magnetic fields by the global dynamo. The consequence of this transition is a decoupling of rotation and magnetism near middle-age, such that magnetic braking can no longer shed angular momentum efficiently and rotation remains almost constant until the subgiant phase. This scenario would also explain the long-period edge in the distribution of rotation periods with B$-$V color for 34,000 stars in the *Kepler* field [25], where significantly longer rotation periods are expected from gyrochronology but not observed for solar-type stars [8, 26]. The fact that the activity level appears to evolve continuously with age suggests that the geometry of the field can change while conserving the magnetic flux [27, 28]. Given the difficulty of obtaining time series measurements of the diminishing rotational modulation in older stars, and considering that their minimal magnetic variability makes a spectroscopic measurement more likely to be representative of the mean activity level, chromospheric activity can thus provide a more reliable age indicator for stars beyond the middle of their main-sequence lifetimes.

The primary objective of this proposal is to use asteroseismic ages determined from TESS observations to calibrate the empirical activity-age relation for solar-type stars. To realize this goal, we will take advantage of an extensive archive of multi-year chromospheric activity measurements from synoptic programs at Mount Wilson and Lowell observatories, the California Planet Search, and other surveys, as well as new asteroseismic modeling tools that have been developed over the past several years (**section 2**). We propose to determine asteroseismic ages and masses for a sample of solar-type stars observed by TESS using archival data through Sector 36 (S36). We will use the publicly available Asteroseismic Modeling Portal (AMP) and grid-based modeling to derive stellar properties with the highest possible precision for each target (**section 3.1**). We propose to use these asteroseismic results to recalibrate the empirical activity-age relation over a range of masses. We will use published spectroscopic parameters ($T_{\rm eff}$, [Fe/H]) to improve the chromospheric activity scale ($\log R'_{\rm HK}$), which was originally calibrated using B$-$V colors at solar metallicity, and we will validate the resulting age scale with published observations of clusters and *Kepler* targets (**section 3.2**). The proposed work will contribute to the objectives of the TESS mission by providing a tool to characterize solar-type stars and their planetary systems (**section 4**), and it will leverage and augment the capabilities of the TESS Asteroseismic Science Consortium (TASC) to benefit the broader community (**section 5**).

2 Technical Approach

In the past, ground-based data on solar-like oscillations emerged slowly enough that we could try to model one star at a time. The *Kepler* mission produced asteroseismic data for hundreds of solar-type targets, and the TESS mission is now yielding similar observations for thousands of bright stars all around the sky. The publicly available stellar model-fitting pipeline that runs behind AMP has recently been updated to use the MESA stellar evolution code and the GYRE pulsation code, incorporating the lessons from *Kepler* to prepare for new data from TESS. We can now apply this updated tool to a sample of bright stars with published multi-year chromospheric activity measurements, using (ultra-)short-cadence TESS data through S36 (**section 2.1**). Our goal is to determine precise asteroseismic ages and masses for these stars from analysis of their solar-like oscillations (**section 2.2**), allowing us to use this sample to recalibrate the empirical activity-age relation over a range of masses. The cornerstone of this model-fitting approach is a global optimization method using a parallel genetic algorithm, which has been made available to the asteroseismology community through the AMP Science Gateway (**section 2.3**).

2.1 TESS Observations of Stellar Activity Targets

The TESS mission is doing for the brightest stars in the sky what *Kepler* did for 100 square degrees in the summer Milky Way. Launched in April 2018, TESS is an all-sky planet search that monitored the brightness of more than 300,000 stars at a cadence sufficient to detect solar-like oscillations in thousands of targets. The baseline mission (S1–S26) observed the southern ecliptic hemisphere in a “step and stare” mode during the first year, followed by the northern ecliptic hemisphere during the second year. Fields near the ecliptic plane were observed continuously for 27 days, while those near the poles (around the continuous viewing zone of JWST) overlapped for an extended time series of up to 1 year duration. The eccentric lunar resonance orbit provides a >95% duty cycle, with data downlink near perigee for 4 hours every 13.7 days. Asteroseismic detections are expected for 6000 nearby stars, including F- and G-type dwarfs and subgiants brighter than V∼7 [10]. In the extended mission (S27–S36), TESS has observed some targets with a 20 second cadence, extending its reach to late-G and early K-type dwarfs. All of these brighter stars are generally much better characterized than the *Kepler* targets—with parallaxes from *Gaia*, as well as additional constraints from ground-based spectroscopy and in some cases interferometry—making asteroseismic analysis potentially even more precise and accurate [29, 30].

Many of the TESS targets have previously had their chromospheric activity levels monitored for decades by synoptic programs designed to discover stellar magnetic cycles. Such cycles are detectable from observations of the intensity of emission in the Ca II H (396.8 nm) and K (393.4 nm) spectral lines (hereafter Ca HK). These lines have long been used as a proxy for the strength and filling factor of magnetic field because the emission traces the amount of non-radiative heating in the chromosphere [31]. The most comprehensive spectroscopic survey for Ca HK variations in solar-type stars was conducted over 35 years from the Mount Wilson Observatory [32, 33]. A similar survey initiated in the 1990’s at Lowell Observatory is now approaching a comparable duration [34]. Additional large archives of multi-year stellar activity measurements have been published from the California Planet

Search [35], the HARPS instrument at La Silla [36], and the SMARTS southern HK project [37], among others.

Obtaining precise asteroseismic ages and masses for stars with published chromospheric activity measurements will enable a fresh investigation into the evolution of stellar activity and magnetic cycles. The fact that stars of a given mass show lower chromospheric activity with age has been established for decades [38]. The TESS data will allow us to establish the relationship between these quantities much more precisely, yielding a tool to determine reliable stellar ages from measurements of chromospheric activity and a suitable mass proxy like $T_{\rm eff}$ or B$-$V color. Recent developments suggest that magnetic cycles exhibit longer periods and lower amplitudes over time, before disappearing entirely or becoming undetectable at activity levels slightly below the equivalent of solar minimum [24]. This may have important implications for dynamo theory, and our understanding of the current evolutionary status of the Sun [39]. Beyond establishing a useful tool to estimate stellar ages, the TESS data will also provide important constraints on this emerging picture.

2.2 Analysis of Solar-like Oscillations

The outer layers of stars like the Sun are convective, with highly turbulent motions carrying heat energy out to the surface where it is radiated away. This churning creates low-frequency sound waves that travel deep into the stellar interior and bring information to the surface in the form of periodic brightness variations. Like a giant musical instrument, the star can resonate not just with one musical note but with an entire symphony of discrete harmonics across a wide range of frequencies. Just as the human ear can easily distinguish between the sound of a violin and a cello from the timbre of their notes, the frequencies exhibited by a star are fundamentally an indication of its size and structure. By passing the signal through a Fourier analysis, we can separate it into the constituent harmonics to reveal more subtle information about the star including its density, composition, and age. Recently the number of main-sequence and subgiant stars known to exhibit these *solar-like oscillations* has increased dramatically. While only a few such data sets were available for detailed modeling just a decade ago, *Kepler* produced suitable observations for hundreds of targets, and TESS is pushing the sample into the thousands.

Solar-like oscillations exhibit a broad envelope of power with a peak frequency $\nu_{\rm max}$ that scales approximately with the surface gravity and effective temperature [40, 41]. Within this envelope, the geometry of each oscillation mode is characterized by a radial order n and spherical degree ℓ, and only the low-degree ($\ell \leq 3$) modes are generally detectable without spatial resolution across the surface (see **Figure 2**). Consecutive radial orders define the so-called large frequency separation $\Delta\nu_0$, which reflects the mean stellar density [42], while the small frequency separation ($\delta\nu_{02}$) between adjacent radial ($\ell = 0$) and quadrupole ($\ell = 2$) modes is sensitive to chemical gradients in the core that reflect the stellar age [43]. The technique of *asteroseismology* attempts to determine the stellar structure and dynamics by interpreting these global oscillations.

For many purposes, the most interesting quantities to emerge from asteroseismic analysis are the stellar radius, mass, and age. For stars with planetary companions, the stellar radius is needed to establish the absolute planetary radius from transit photometry. The mass provides the absolute scale of the orbit, and when combined with radial velocity mea-

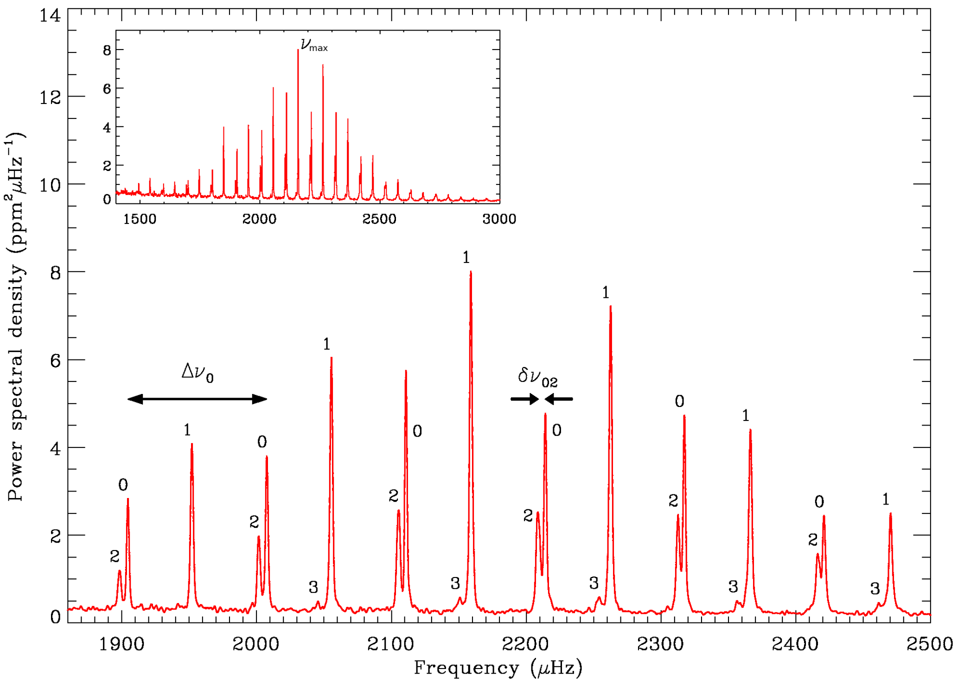

Figure 2: *Solar-like oscillations in the bright star 16 Cyg A as observed by Kepler, showing the characteristic large and small frequency separations* $\Delta\nu_0$ *and* $\delta\nu_{02}$*. The frequency of maximum oscillation power* $\nu_{\rm max}$ *is indicated in the inset.*

surements yields the absolute mass of the planet. The age is important for assessing the dynamical stability of the system and establishing its chronology with respect to other planetary systems. For relatively faint stars, where only $\nu_{\rm max}$ and $\Delta\nu_0$ can be determined from the observations, empirical scaling relations can be used in conjunction with the effective temperature ($T_{\rm eff}$) to estimate the stellar radius and mass. Comparisons with stellar models can use additional information from ground-based spectroscopy ($\log g$, [Fe/H]) to provide more precise estimates of the radius and mass, along with constraints on the age of the star (and its planetary system). The most precise constraints on all of these properties—as well as information about the interior composition and structure—come from models that match the individual oscillation frequencies.

2.3 Asteroseismic Modeling Portal

Anticipating the flood of observations that *Kepler* would produce for stars like the Sun, over the past 15 years a method was developed for the automated interpretation of solar-like oscillations. The idea was to teach a supercomputer how to model the observations as well as the experts, but to do it automatically and consistently using state-of-the-art tools. The effectiveness of the technique was initially demonstrated using observations of the Sun [44], and it was made available through a community website called AMP [45]. The approach was subsequently validated using some of the best asteroseismic observations to emerge from *Kepler* [46, 47], and since then it has been applied to many other stars [48, 49, 50] including dozens with planetary systems [51, 52, 53, 54, 55, 56, 57, 58, 59, 60].

The stellar model-fitting pipeline that runs behind AMP optimizes four adjustable parameters, including the stellar mass (M) from 0.75 to 1.75 $M_\odot$, the metallicity (Z) from 0.002 to 0.05 (equally spaced in $\log Z$), the initial helium mass fraction (Y_i) from 0.22 to 0.32, and the mixing-length parameter (α) from 1.0 to 3.0. The stellar age (t) is optimized internally during each model evaluation by matching the observed value of $\Delta\nu_0$, which decreases almost monotonically from the zero age main-sequence (ZAMS) to the base of the red giant branch [61]. The underlying genetic algorithm [GA; 62, 63] uses two-digit decimal encoding, so there are 100 possible values for each parameter within the ranges specified above. Each run of the GA evolves a population of 128 models in parallel through 200 generations to find the optimal set of parameters, and four independent runs are executed in parallel with different random initialization to ensure that the best model identified is truly the global solution. The method requires about 10^5 model evaluations, compared to 10^8 models for a complete grid at the same sampling density, making the GA nearly 1000 times more efficient than a complete grid (currently one day of computing time, compared to a few years for a grid). Of course, a grid can in principle be applied to hundreds of observational data sets without calculating additional models—but the GA approach also provides the flexibility to improve the physical ingredients over time, while the physics of a grid are fixed.

Over the past several years, this stellar model-fitting pipeline was updated in preparation for TESS. After improving the statistical methods used by the GA, a streamlined version of the open-source Modules for Experiments in Stellar Astrophysics (MESA) stellar evolution code was developed, which is called Embedded MESA (EM). The GA was adapted to interface with EM and the GYRE pulsation code [64], and full-scale optimization tests were completed using solar data. These tests involved running hybrid MPI-OpenMP jobs on an XSEDE supercomputer. Each job is an MPI parallel instance of the GA, which spawns an ensemble of 128 tasks. Each task is a 4-core OpenMP parallel instance of a stellar model produced by EM and GYRE, so each job runs on 512 cores and requires about 12 hours to complete. For a *Kepler*-like set of observational constraints for the Sun, this pipeline recovers optimal stellar properties consistent with the solar values. It has subsequently been applied to several stars observed by TESS [65, 66, 67, 68].

3 Proposed Research

The development of AMP and its application to a wide variety of *Kepler* targets has demonstrated the potential of asteroseismology to yield precise stellar properties. This is particularly important for exoplanet host stars, because the derived asteroseismic radius, mass, and age can provide useful constraints on the properties of the associated planetary systems. Matching individual oscillation frequencies typically improves the precision by a factor of two or more over pipelines that only use the global oscillation properties [49], and the uniform analysis method produces an ensemble of results that can probe broader questions about the formation and evolution of stellar and planetary systems. In particular, asteroseismic ages can now be used as fundamental anchors for empirical relations describing how chromospheric activity declines over time. This will ultimately allow stellar ages to be determined for TESS targets that are too faint for asteroseismology, and for older systems where other age proxies like rotation begin to break down. We propose to establish a tool over the next three years that can be used to determine the ages of solar-type stars and their planetary systems from activity measurements, which will involve:

- **Phase 1:** Deriving asteroseismic ages and masses with the highest possible precision from TESS observations of bright stars that have had their chromospheric activity levels monitored for decades. This work will benefit from the coordinated activities of the Europe-based TASC collaboration, while augmenting their capabilities with cutting-edge modeling techniques.

- **Phase 2:** Recalibrating the empirical activity-age relation over a range of masses, folding in improvements to the activity scale that arise from the well-characterized sample. This will leverage the published archive of ground-based observations to establish a reliable age scale from the TESS results, which can then be applied to a broader range of systems.

Our experience deriving asteroseismic properties from *Kepler* data and analyzing stellar activity measurements suggests that we will be able to complete this work during the proposed timeline. We provide details for these two phases of the project in the subsections below.

3.1 Determining Asteroseismic Ages from TESS Data

Our target list is drawn from 1339 bright stars with published multi-year data on chromospheric activity from the Mount Wilson and Lowell surveys, the California Planet Search, as well as smaller samples from other surveys. We focus the short-cadence (2-minute) sample on 597 hotter stars by requiring the B$-$V color to be between 0.5 and 0.7, corresponding to spectral types between F8 and G6. Magnetic braking is ineffective in stars hotter than F8, while solar-like oscillations for most stars cooler than G6 will not be detectable with 2 minute time-series from TESS. We supplement these hotter targets with an ultra-short-cadence (20-second) sample observed during the extended mission (S27–S36), which includes 391 stars with a B$-$V color between 0.7 and 0.9 to reach the late G- and early K-type stars. These cooler targets oscillate at higher frequencies and have lower intrinsic amplitudes, so faster sampling is required for a detection. However, the hotter stars can also benefit from the 20-second observing mode because the elimination of onboard cosmic ray rejection increases the effective integration time by 20%, and the higher Nyquist frequency avoids attenuation of the signal by up to 30% for solar twins.

Sufficient data already exist in the TESS public archive (through S36) for 465 short-cadence and 60 ultra-short-cadence targets, which defines our proposed sample. Using data from the TESS Input Catalog [TIC; 69], we calculated the probability of detecting solar-like oscillations for each of these 525 targets using a prescription developed for *Kepler* [70]. From this analysis, we expect a total asteroseismic sample of up to 221 stars, including 156 with a detection probability >75%. *In the first phase of the project, we will use AMP to derive the precise asteroseismic age and mass for bright stars that show individual oscillation frequencies, and grid-based modeling to characterize the fainter targets with global oscillation properties.*

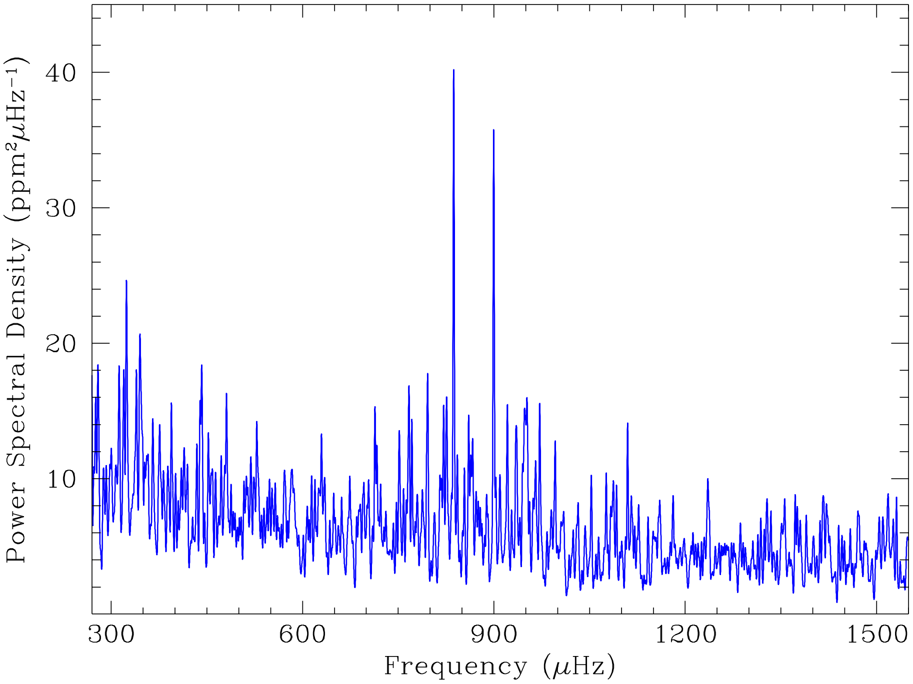

Figure 3: *Asteroseismic detection for the Mount Wilson target 94 Aqr from TESS observations in S2. The frequency of maximum power is 862 μHz, and the large frequency separation is 50.3 μHz in this G8 subgiant. Analysis of the power spectrum identified more than a dozen individual frequencies for detailed modeling with AMP, yielding* $M = 1.22 \pm 0.03\,M_\odot$ *and* $t = 6.2 \pm 0.2$ *Gyr.*

3.1.1 Detailed Modeling of Individual Frequencies with AMP

Asteroseismic analysis relies on the 2-minute or 20-second observations, for which target pixel files and light curves have been delivered to MAST by the Science Processing and Operations Center (SPOC). Light curves optimized for asteroseismology are subsequently made available through the TESS Asteroseismic Science Operations Center (TASOC). For a few of the brightest targets, the saturated bleed columns will not be fully captured within a standard pixel mask. These will require a custom mask surrounding the star, from which light curves can be obtained using the unsaturated pixels in the wings of the PSF (halo photometry), a technique originally developed for *K2* [71] that has now been adapted for TESS. For targets with the highest signal-to-noise ratio (S/N), we will fit the power spectra of the (ultra-)short-cadence light curves using a Bayesian MCMC fitting code [72] to provide individual mode frequencies for detailed stellar modeling with AMP.

As an example of the capabilities of AMP for one of the stars in our sample, we can look at results from an analysis of the Mount Wilson target 94 Aqr. This triple-system was observed by TESS for 27 days in S2, and a power spectrum of the TASOC light curve shows a clear detection of solar-like oscillations from the G8 subgiant (see **Figure 3**). The other two components of the system are both K dwarfs, which exhibit oscillations with a timescale and amplitude that are not detectable with 2-minute sampling. Several teams within TASC attempted to identify the individual oscillation modes from this power spectrum, resulting in a list of more than a dozen unambiguous frequencies. Using these asteroseismic constraints as inputs, along with spectroscopic parameters ($T_{\rm eff}$, [Fe/H]) from the literature [73] and a luminosity derived from the *Gaia* DR2 parallax, AMP determined a precise mass and age for the subgiant ($M = 1.22 \pm 0.03\,M_\odot$, $t = 6.2 \pm 0.2\,$Gyr). The asteroseismic age is slightly younger than predicted from a standard empirical activity-age relation [38], and substantially more precise. *We will perform a similar analysis for each of the stars in our sample with individual frequencies detected by TESS—a computationally intensive task requiring about 1 million CPU-hours in total.*

3.1.2 Grid-based Modeling of Global Oscillation Properties

During the first year of the *Kepler* mission, 2000 solar-type stars were monitored at 1-minute cadence for 30 days each. Solar-like oscillations were detected down to V∼12 in about 30–35% of the targets, while individual frequencies could be identified in about 5–10%. Similar detections are expected from TESS down to V∼7 [11], particularly in late F-type and early G-type stars which have larger intrinsic oscillation amplitudes. Considering our total sample of 525 stars in the TESS public archive through S36, we can expect to obtain individual frequencies for 30–50 stars. For the remaining 100–130 detections with lower S/N, we will determine the global oscillation properties ($\nu_{\rm max}$, $\Delta\nu$) to provide inputs for grid-based modeling. The frequency of maximum oscillation power ($\nu_{\rm max}$), obtained from a Gaussian fit to the smoothed power spectrum, is related to the surface gravity and effective temperature. The large frequency separation ($\Delta\nu$), derived from autocorrelation of the power spectrum, scales with the mean stellar density.

A grid of stellar models has been generated using the MESA code configured with the same input physics employed by AMP. This grid has been coupled to an updated implementation of the SEEK method [74] to determine the optimal stellar properties and their uncertainties for each of our targets. Initial results from grid-based modeling of the *Kepler* sample [75] did not have the benefit of spectroscopic parameters or precise parallaxes from *Gaia*. The addition of those constraints to more recent grid-based modeling efforts [76] resulted in substantially more precise and accurate stellar properties, in particular the ages and masses. *We will perform grid-based modeling for each of the stars in our sample that have global oscillation properties detected by TESS, including spectroscopic parameters compiled from the literature and luminosity constraints derived from Gaia EDR3 parallaxes.*

3.2 Calibrating an Empirical Activity-Age Relation

The discovery that rotation is less useful as a diagnostic of age beyond the middle of stellar main-sequence lifetimes is disappointing, but the other empirical relation (activity-age) does not appear to be similarly disrupted. The angular momentum loss due to magnetic braking has a strong dependence on field geometry, with roughly 80% attributed to the dipole field which has a much larger Alfvén radius than higher-order fields [12]. Consequently, a shift in the geometry of the magnetic field—from global scales like the dipole to smaller scales like the closed loops surrounding active regions—can effectively decouple the evolution of rotation and magnetism near middle-age as observed in the *Kepler* sample [6, 21]. This decoupling is fortunate, because it suggests that we can continue using chromospheric activity as a

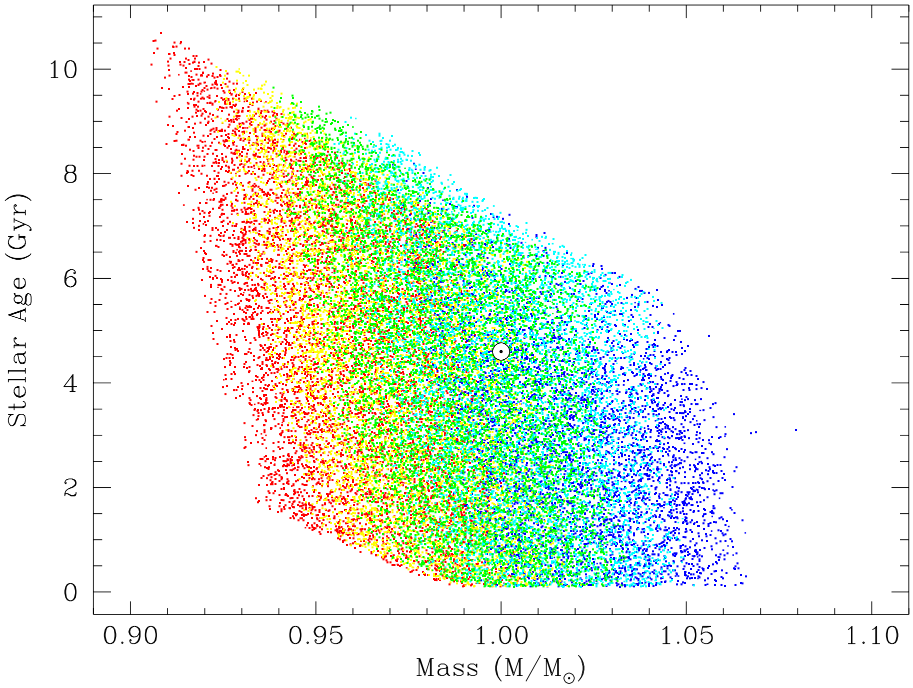

Figure 4: *The full range of masses and ages sampled by spectroscopic solar twins. Models were selected randomly from MIST tracks to have* T_{eff} *within* ±100 K, $\log g$ *and [M/H] within* ±0.1 *dex of solar values. Color indicates metallicity, with five bins from [M/H]* = −0.1 *(red) to* +0.1 *(blue). All stars older than* ∼7 *Gyr are less massive than the Sun, and often have lower metallicity, biases that may complicate inferences of evolutionary behavior.*

reliable proxy for the age through the entire main-sequence lifetimes of stars. We just need to calibrate the empirical relation using a reliable source for the stellar ages.

A first step in this direction was recently taken [9], using a Bayesian analysis of stellar isochrones for a sample of 60 spectroscopic solar twins to determine a range of ages from 0.5 to 9 Gyr. The reliability of the isochrone ages was improved by the availability of *Gaia* DR2 parallaxes for the targets, but there was still a false-alarm probability >1% for stars older than 6–7 Gyr. Like previous investigations, the solar twin sample was defined by requiring the spectroscopic parameters to be within observational tolerances of the current solar effective temperature, surface gravity, and metallicity ($T_{\text{eff}} \pm 100$ K, $\log g$ and [Fe/H] ±0.1 dex). However, the extension of this approach to *solar analogs* across a range of ages is not completely reliable, because all of the spectroscopic parameters change on stellar evolutionary timescales. Solar-calibrated models are cooler at younger and older ages, the surface gravity decreases monotonically with age, and the observed metallicity is reduced over time due to diffusion and settling. Consequently, any sample of spectroscopic solar twins that span a range of ages will have biases in the mass and metallicity distributions that may complicate inferences of evolutionary behavior (see **Figure 4**). In particular, spectroscopic solar twins older than ∼7 Gyr are all less massive than the Sun, and often have lower metallicity. *In the second phase of this project, we will use an improved activity scale from published spectroscopic measurements and the more reliable asteroseismic results from TESS to recalibrate the empirical activity-age relation over a range of masses.*

3.2.1 Improving the Activity Scale with Spectroscopic Parameters

The chromospheric activity scale ($\log R'_{\rm HK}$) relies on direct measurements of emission in the cores of the Ca HK lines, and on a normalization to account for differences in bolometric luminosity. The direct measurements are usually tabulated as the so-called *S-index*, the ratio of flux in the Ca HK line cores to that in nearby pseudo-continuum bands [77]. The normalization allows meaningful comparisons of stars with different spectral types, and its functional dependence on B−V color dates back to 1984 [78]. Recognizing that the B−V color was used as a proxy for $T_{\rm eff}$ and [Fe/H], it makes sense to revisit the calibration of both the photospheric contribution to flux in the Ca HK line cores, as well as the normalization of the bolometric flux in the pseudo-continuum bands. An updated activity scale based on $T_{\rm eff}$ is strongly correlated with the scale based on B−V color, but it has an improved sensitivity to evolutionary changes at the lowest activity levels ($\log R'_{\rm HK} < -5$) indicative of older stars [9]. The stars in the solar twin sample are all near solar metallicity, but a sample with a broader range of metallicities can benefit from a similar analysis that considers dependencies on both spectroscopic parameters [79]. *We will use the published spectroscopic parameters for our sample to improve the chromospheric activity scale, following the procedures outlined in [9] and [79], taking care to remove spectroscopic binaries.*

3.2.2 Validating the Age Scale with Clusters and Kepler Targets

With an improved activity scale from the analysis described above, as well as precise asteroseismic ages and masses from TESS observations, we will finally be in a position to recalibrate the empirical activity-age relation over a range of masses (i.e. fit new power laws using the updated activity levels and asteroseismic ages). We don't know the intrinsic range of ages and masses within our sample, but with 156 expected detections we can construct subsamples of about 40 stars in each of four mass bins from 0.85 to 1.25 $M_\odot$ with ΔM=0.1 (comparable to the mass range adopted in [9], but using precise asteroseismic masses instead of spectroscopic parameters). On average, this will provide asteroseismic anchors for the empirical activity-age relations at intervals of 0.35 Gyr for solar-type stars. The sampling will be slightly better for more massive stars that have shorter main-sequence lifetimes, and slightly worse for stars less massive than the Sun with oscillations that are more difficult to detect. The range of ages for spectroscopic solar twins is sampled more densely [9], but the age precision from isochrone fitting will always be inferior to what can be achieved after incorporating asteroseismic constraints [2]. Several dozen stars from the spectroscopic solar twins sample are within the asteroseismic detection limits of TESS, so a direct comparison of the asteroseismic and isochrone age scales will be possible.

Asteroseismic ages from *Kepler* and TESS for several targets with chromospheric activity levels that have been recalibrated using $T_{\rm eff}$ [9] and approximately corrected for non-solar metallicity [79] (**blue points in Figure 1**) generally agree with the empirical relation for solar analogs. Note that stars with similar ages and masses (such as the Sun and ζ Tuc) have similar activity levels, while stars with similar ages but significantly different masses (such as α Men and 94 Aqr, at 0.94 $M_\odot$ and 1.22 $M_\odot$) show a significant spread in activity. This supports the notion that the spread in the activity-age relation is likely related to a spread in stellar mass and thus convection zone depth, analogous to the mass-dependence of gyrochronology relations. Subsets of the *Kepler* sample, selected by asteroseismic mass, can be used to validate the age scale that emerges from the TESS sample. This will be supplemented with published cluster data at the young end, where the *Kepler* sample is more limited, using the B−V color of cluster members as the mass proxy. *We will use published observations of older stars from Kepler as well as younger clusters to validate the age scale from our recalibration of the empirical activity-age relation.*

4 Impact & Relevance

By the end of this project, we will have established a new tool to determine reliable ages for stars and their planetary systems based on B−V colors, spectroscopic parameters ($T_{\rm eff}$, [Fe/H]) and chromospheric activity levels ($\log R'_{\rm HK}$). For four different mass bins ($M = 0.9, 1.0, 1.1, 1.2\,M_\odot$), calibrated with precise asteroseismic masses but parametrized by $T_{\rm eff}$ or B−V color for application to other stars, this tool will incorporate the power law relationships between chromospheric activity and asteroseismic age that we establish using the techniques described above. We can immediately apply this tool to the 800+ stars in our sample that have published chromospheric activity levels, but for which asteroseismic detections from TESS data are not expected. More generally, this tool will be useful to establish ages for fainter stars where asteroseismology is not feasible, particularly the older systems where methods based on rotation begin to break down. We expect a substantial improvement over the current activity-age relation for solar-mass stars [9], both by using the more precise asteroseismic ages for the calibration, and by extending the relation to cover a range of masses (not just solar twins). Our timeline is designed to maximize the science return from the TESS mission, but our new tool will also be useful for analyses of *Kepler* and *K2* targets whenever chromospheric activity measurements become available.

The research described in this proposal addresses NASA's **Strategic Goal 1**, as defined in the 2018 Strategic Plan: "Expand human knowledge through new scientific discoveries". In particular, it contributes to **Strategic Objective 1.1**: "Understand the Sun, Earth, Solar System, and Universe", including two specific core contexts:

- **Discovering the Secrets of the Universe**: "understand the Sun and its effects on the solar system, the Earth, other planets and solar system bodies, the interplanetary environment, the space between stars in our galaxy, and the universe beyond." (Asteroseismic analysis of TESS targets will probe the fundamental physical processes that operate in the Sun under a broader range of physical conditions).
- **Searching for Life Elsewhere**: "Are we alone? [This] is a central research question that involves... the thousands of potentially habitable worlds around other stars. This research supports a fundamental science topic at the interface of physics, chemistry, and biology." (Measuring the evolution of stellar activity with age for exoplanet host stars will help assess the potential for life in distant solar systems).

The TESS mission is designed to discover nearby planetary systems around some of the brightest stars in the sky. The research outlined in this proposal will enable the characterization of some bright exoplanet host stars with asteroseismology. This is essential to convert precise transit photometry into an absolute radius for the planetary body. In addition, accurate ages from the recalibrated empirical activity-age relation will provide important clues about the formation and evolution of the planetary systems. The determination of accurate stellar properties for a broad array of solar-type stars will stimulate new insights about stellar structure and evolution, and will provide a broader context for our understanding of the Sun and our own solar system.

5 Plan of Work

The work outlined in this proposal will comprise the primary research effort for the PI, whose position as a Research Scientist relies entirely on grants. The AMP Science Gateway is supported by computational resources from XSEDE (formerly the TeraGrid). More than 13 million CPU-hours of computing time have been allocated to AMP since 2009 for the asteroseismic analysis of *Kepler* and TESS targets, including 2 million CPU-hours awarded in 2021 to support TASC projects. Annual allocation requests are submitted by the AMP administrator each January for time beginning in April, with supplement requests considered every three months.

5.1 Key Milestones

We expect that the first phase of this project (asteroseismic properties from TESS data) will require a total of 24 months to complete, while the second phase (recalibration of the empirical activity-age relation) will require about 12 months. These estimates include publication of the results in a refereed journal and presentation at a scientific conference. The key milestones during each year will be:

- **Year 1:** Identify and extract individual oscillation frequencies for 30–50 targets with the highest S/N (Q1-Q3), perform detailed modeling with AMP (Q2-4), and prepare the results for publication (Q4).
- **Year 2:** Derive global oscillation properties for 100–130 targets with lower S/N (Q1-Q3), perform grid-based modeling as the global oscillation properties become available (Q2-4), and prepare the results for publication (Q4).
- **Year 3:** Use the spectroscopic parameters of the sample to improve the activity scale (Q1-2), divide the sample into asteroseismic mass bins and calibrate the updated activity-age relations (Q2-3), validate the resulting age scale using published activity data for clusters and *Kepler* targets with known ages (Q3-4), and prepare the results for publication (Q4).

Our experience with the analysis and interpretation of comparable samples of *Kepler* targets suggests this is a reasonable timeline. These milestones only rely on data that are currently available in the TESS public archive (through S36), with spectroscopic and validation data obtained from published results.

5.2 Management Structure

The PI will fully coordinate activities with the two Collaborators on tasks relevant to their expertise. The collaboration will be conducted primarily through a Slack channel and by email, with occasional gatherings at conferences.

- **PI:** will be responsible for prioritizing the targets for data analysis (with Collaborator#2), will participate in the grid-based modeling (with Collaborator#1), perform the detailed modeling of individual frequencies with AMP, and lead the effort to recalibrate the empirical activity-age relation. The PI will also be responsible for overall project management, and the interpretation, publication and presentation of results.
- **Collaborator#1:** will work with the PI on grid-based modeling, using the same input physics that are used for detailed modeling by AMP, and will also assist in the interpretation and publication of results.
- **Collaborator#2:** will help coordinate the data analysis through TASOC for the stellar activity targets, as prioritized by the PI, and will also assist in the interpretation and publication of results.

5.3 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. The role of the project will be to prioritize the analysis of our 525 stellar activity targets through the TASC working group on solar-like oscillations. Additional data derived from these products 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 as machine-readable tables in the resulting publications and released as supplementary materials through the journal. The empirical activity-age relation which results from this project will be released as python code on GitHub by the end of the award.

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