Project Summary

The stellar Rossby number is a key parameter that is related to both the magnetic evolution of stars and the space weather environment of their planetary systems. It is traditionally estimated as the ratio of the stellar rotation period to the convective turnover time. While the rotation period can often be inferred directly from observations, the convective turnover time depends on properties of the stellar interior that can only be determined indirectly from stellar models. Asteroseismic analysis of space-based photometry can yield precise values for all of the stellar properties that are required to estimate the convective turnover time, including the depth of the surface convection zone as well as the stellar radius, mass, and luminosity. We propose to calibrate the convective turnover time as a function of Gaia color and spectroscopic parameters, using stellar properties derived from asteroseismic analysis of data obtained by NASA's Kepler and TESS missions.

Our asteroseismic calibration sample includes more than 100 main-sequence targets and 44 subgiant stars observed by the Kepler and TESS missions, allowing us to extend the calibrated range of Gaia color relative to previous efforts, and to quantify the influence of lower surface gravity. Asteroseismic analysis relies on short-cadence observations, for which target pixel files and light curves have been delivered to MAST by the Science Processing and Operations Center (SPOC). From a power spectrum of these short-cadence light curves, we will determine the individual oscillation frequencies for each of our new targets. Asteroseismic radii, masses, and convection zone depths will be derived from detailed modeling, using the observational inputs obtained from Kepler and TESS data along with spectroscopic constraints from the PASTEL catalog and luminosities from Gaia DR3.

The proposed work will establish a new tool to determine a reliable Rossby number for solar-type stars using only the rotation period, Gaia color, and spectroscopic parameters. The traditional calibration of the Rossby number is based on B−V color, and ignores possible dependencies on surface gravity and metallicity. By anchoring our new calibration on asteroseismic inferences of stellar structure and quantifying the influence of additional spectroscopic parameters, we will enable more reliable studies of magnetic and rotational evolution for solar-type stars as well as the space weather environment of their planetary systems.

Asteroseismic calibration of the stellar Rossby number

Contents

1 Significance & Objectives

The stellar Rossby number (Ro) is a key parameter that is related to both the magnetic evolution of stars and the space weather environment of their planetary systems. Generally, it is a dimensionless number that is used in the description of fluid flows. In the context of stellar evolution, it characterizes the relative importance of Coriolis forces on convective motions—low values of Ro correspond to flows that are strongly influenced by rotation, while higher values indicate flows that are dominated by turbulence. At moderate values of Ro, the imprint of Coriolis forces on the convective patterns is sufficient to establish solar-like differential rotation, with an equator that rotates faster than the poles. The resulting shear is one ingredient of the global stellar dynamo, which organizes magnetic fields on the largest spatial scales. Thus, the value of Ro is central to understanding magnetic stellar evolution.

From an observational perspective, the Rossby number is traditionally estimated as the ratio of the stellar rotation period to the convective turnover time (Ro $\equiv P_{\rm rot}/\tau_c$). While the rotation period can often be inferred directly from observations, the convective turnover time depends on properties of the stellar interior that can only be determined indirectly from stellar models. Furthermore, the value of τ_c depends on the location within the convective envelope of a solar-type star, generally increasing with depth. Consequently, the dimensionless Rossby number can have different absolute values depending on whether τ_c is defined at a specific location (e.g. near the base of the convective envelope), or if a global average over the entire convection zone is adopted [1]. However, the absolute value of Ro is less important than how it scales with stellar mass, because removing the mass-dependence of activity proxies is the primary advantage of using Ro rather than $P_{\rm rot}$ (see **Figure 1**).

The most widely used approach to estimate the convective turnover time was developed more than 40 years ago [2]. Exploiting the fact that stellar activity levels are correlated with Ro, this approach used the chromospheric activity levels and rotation periods for 41 main-

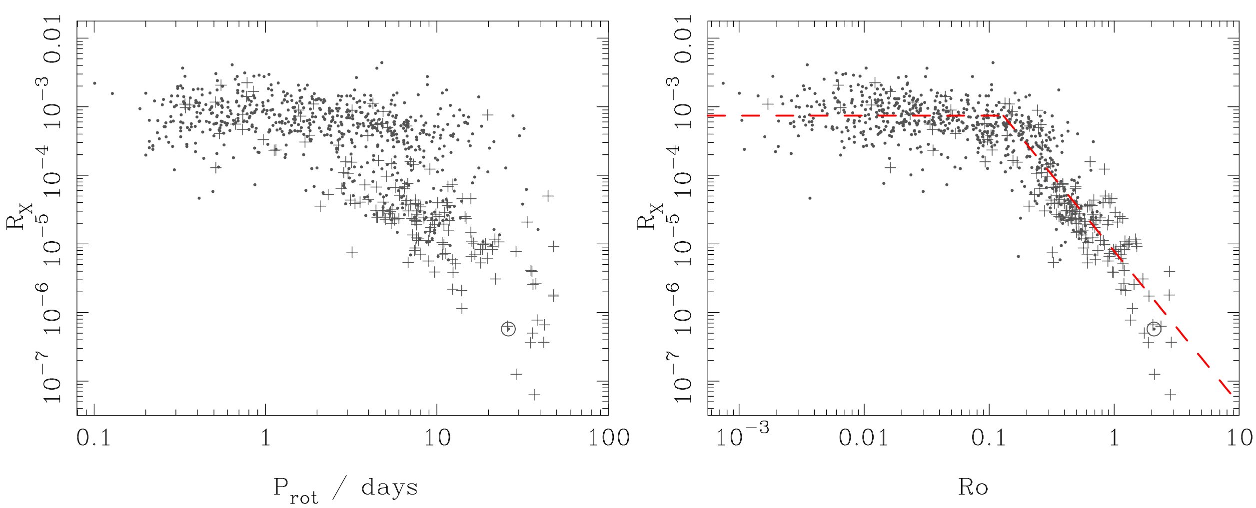

Figure 1: *Ratio of X-ray to bolometric luminosity plotted against rotation period (left) and Rossby number (right). Stars known to be binaries are shown as + symbols, and the Sun is indicated with the ⊙ symbol. In normalizing $P_{\rm rot}$ by τ_c, the Rossby number effectively removes the mass-dependence to define a clearer activity-rotation relation (red dashed line).*

sequence FGK stars observed by the Mount Wilson survey to fit a semi-empirical relation between $\log \tau_c$ and B−V color. Decades later, a similar analysis of 824 solar-type stars with measured X-ray luminosities and rotation periods derived a comparable relation between τ_c and V−K color [3]. Importantly, this analysis extended the relation to M dwarfs, which were not included in the Mount Wilson survey. However, both of these semi-empirical relations rely on relatively indirect constraints on stellar evolution models, and yield values of τ_c for the Sun that are inconsistent with standard solar models.

Recently, a new approach was pioneered using asteroseismic models for 62 stars with solar-like oscillations detected by the *Kepler* mission to calibrate a relation between τ_c and *Gaia* $\mathrm{G_{BP}}-\mathrm{G_{RP}}$ color [4]. This analysis relied on asteroseismology to yield precise values for all of the stellar properties that are required to estimate τ_c directly, including the depth of the surface convection zone as well as the stellar radius, mass, and luminosity: $\tau_c \simeq d_{cz}(M/LR)^{1/3}$. The approach yielded a very good estimate of the local convective turnover time at the base of the stellar convection zone—matching the value for the Sun obtained from a fully calibrated standard solar model [5]. Given the promising results from this initial exploration, there are several possibilities to improve it—including expansion of the calibration sample, adoption of extinction-corrected colors for the relatively distant *Kepler* targets, and consideration of additional dependencies on spectroscopic properties such as surface gravity and metallicity. **These potential improvements in the asteroseismic calibration of convective turnover time are the main focus of this proposal.**

There is renewed interest in the stellar Rossby number, motivated by recent observations of the rotational and magnetic evolution of old solar-type stars. The first indications of unexpected behavior came from the *Kepler* mission, which found anomalously fast rotation among older field stars with asteroseismic ages [6]. This peculiarity was subsequently confirmed with the best characterized *Kepler* asteroseismic targets, and a model was proposed to explain the observations with significantly weakened magnetic braking beyond a critical Rossby number [7]. 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 with age while the rotation rate remains almost constant [8]. 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 [9, 10]. A coincident shift in stellar dynamo properties was later identified, with the activity cycle period growing longer and the amplitude becoming smaller at nearly constant rotation [11].

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 at a critical Rossby number, 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 [12, 13], where significantly longer rotation periods are expected from standard spin-down models but not observed for solar-type stars [14, 15]. 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 [16, 17]. Ground-based spectropolarimetry supports this conclusion, suggesting that the wind braking torque abruptly decreases by more than an order of magnitude at a critical Rossby number [18, 19], and continues to diverge from standard spin-down models at higher Ro (e.g., see Figure 4). These results motivate a fresh look at the asteroseismic calibration of Ro.

The primary objective of this proposal is to calibrate the convective turnover time as a function of *Gaia* color and spectroscopic parameters. To realize this goal, we will take advantage of archival data obtained by NASA's *Kepler* and TESS missions, as well as new asteroseismic modeling tools that have been developed over the past several years (**section 2**). We propose to determine updated asteroseismic radii, masses, and convection zone depths for a sample of more than 100 stars, using observational inputs obtained from *Kepler* data along with spectroscopic constraints from the PASTEL catalog and luminosities from *Gaia* DR3. We will use the publicly available Asteroseismic Modeling Portal (AMP) to derive stellar properties with the highest possible precision for each target (**section 3.1**). We propose to expand the calibration sample by performing a similar asteroseismic analysis of nearby main-sequence stars observed by TESS through Sector 76 (S76), as well as subgiants observed by *Kepler* and TESS to sample redder colors and lower surface gravities (**section 3.2**). We propose to use these asteroseismic results to produce an improved calibration of the convective turnover time, using extinction-corrected colors from *Gaia* DR3 and a multivariate Bayesian analysis of additional dependencies on spectroscopic parameters (**section 3.3**). The proposed work will contribute to NASA's objectives 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 [20], incorporating the lessons from *Kepler* to prepare for new data from TESS. We can now apply this updated tool to archival data sets from *Kepler* and recent asteroseismic detections from TESS data through S76 (**section 2.1**). Our goal is to determine precise asteroseismic properties for these stars from analysis of their solar-like oscillations (**section 2.2**), allowing us to use this sample for an improved calibration of the convective turnover time. 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 Archival Data from Kepler and TESS

In 2009, the *Kepler* mission revolutionized the quantity and quality of data that were available for asteroseismic analysis. For four years, it stared at a single 100 square degree field of view and monitored the brightness of more than 150,000 stars every 30 minutes [21]. A subset of 512 stars at any given time were monitored with a shorter 1-minute cadence, sufficient to detect solar-like oscillations in main-sequence stars. More than 2000 dwarfs and subgiants were targeted for short-cadence observations in the first year of the mission, yielding more than 500 detections of solar-like oscillations [22]. About 100 of the best and brightest targets were selected for continued short-cadence monitoring during the remainder of the mission, yielding unprecedented asteroseismic data sets. Substantial efforts have already gone into the characterization of solar-like oscillations from archival *Kepler* data, including a "LEGACY" sample of 66 main-sequence stars [23] as well as the smaller "KOI" sample of 35 solar-type stars with transiting exoplanets or planet candidates [24]. Most of these data sets have not yet been analyzed with the latest generation of asteroseismic modeling tools.

The TESS mission is doing for the brightest stars in the sky what *Kepler* did for a small patch of the summer Milky Way [25]. Launched in 2018, TESS is an all-sky planet search that has 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. In the extended mission (S27 and beyond), TESS began to observe some targets with a 20-second cadence, extending its reach to late-G and early K-type dwarfs [26]. An asteroseismic survey of the first 3.5 years of TESS observations detected solar-like oscillations in 4177 main-sequence and subgiant stars, including 486 from 20-second cadence data [27]. These brighter stars are generally much better characterized than the *Kepler* targets—with precise parallaxes from *Gaia*, and additional constraints from high-resolution spectroscopy—making asteroseismic analysis potentially even more accurate [28, 29].

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 prior to 2010, *Kepler* produced suitable observations for hundreds of targets, and TESS is now 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 [30, 31]. Within this envelope, the geometry of each oscillation mode is characterized by a radial order n and

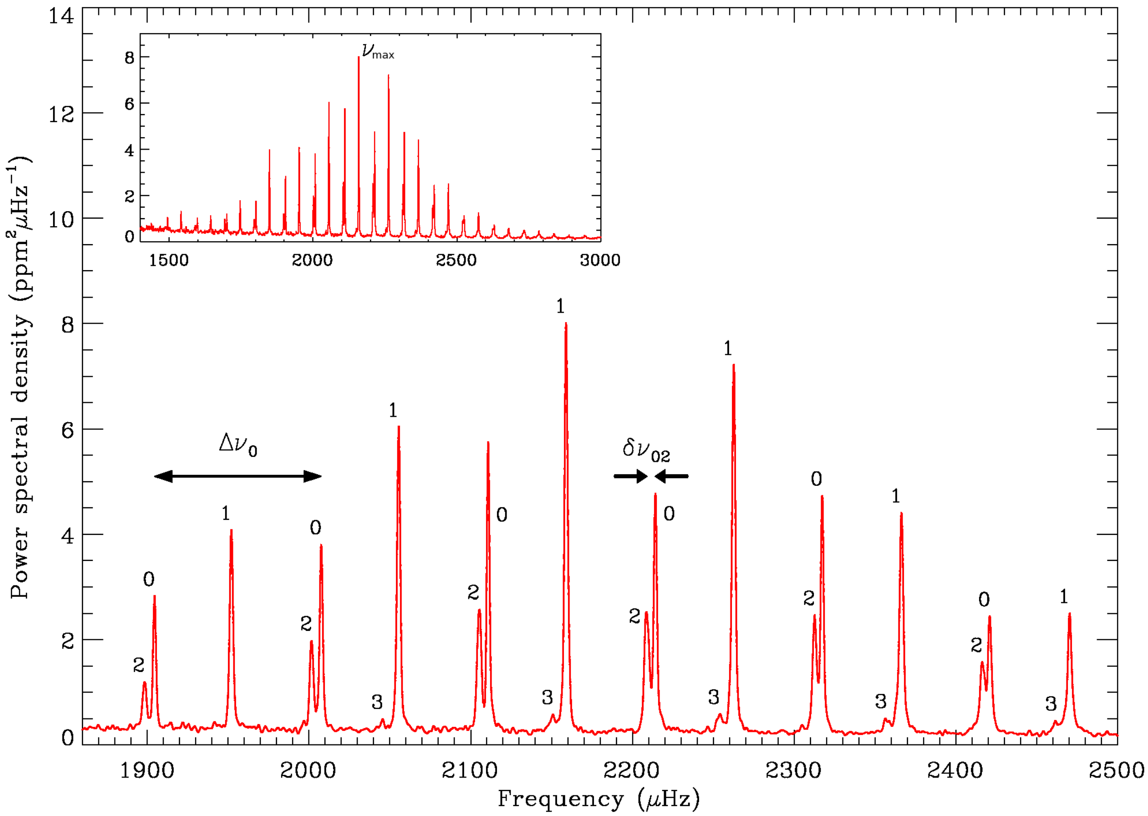

Figure 2: *Solar-like oscillations in the bright star 16 Cyg A as observed by Kepler, showing the characteristic large and small frequency separations $\Delta\nu_0$ and $\delta\nu_{02}$. The frequency of maximum oscillation power $\nu_{\rm max}$ is indicated in the inset [adapted from 34].*

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 [32], 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 [33]. 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 measurements 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 [35], and it was made available through a community website called AMP [36]. The approach was subsequently validated using some of the best asteroseismic observations to emerge from *Kepler* [37, 38], and since then it has been applied to many other stars [39, 40, 41, 42] including dozens with planetary systems [43, 44, 45, 46, 47, 48, 49, 50, 51, 52].

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 [53]. The underlying genetic algorithm [GA; 54, 55] 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 new data from the TESS mission. 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 [56], 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 [20]. It has subsequently been applied to several stars observed by TESS [57, 58, 59, 60] including some with planetary systems [61, 26, 62, 19].

3 Proposed Research

The development of AMP and its application to a wide variety of *Kepler* and TESS 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 [40], 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 properties (including the depth of the surface convection zone) can now be used to calculate the convective turnover time τ_c [4]. This will ultimately allow the stellar Rossby number (Ro) to be determined for *Kepler* and TESS targets that are too faint for asteroseismology, opening a new window on rotational and magnetic evolution. We propose to establish a tool over the next three years that can be used to determine Ro from a rotation period, *Gaia* color, and spectroscopic parameters, which will involve:

- **Phase 1:** Deriving radii, masses, and convection zone depths with the highest possible precision using two well-characterized samples of *Kepler* asteroseismic targets. This work will leverage existing solar-like oscillation frequencies determined for more than 100 stars, combining them with published spectroscopic parameters and *Gaia* luminosity constraints for high-fidelity modeling with the latest version of AMP.

- **Phase 2:** Expanding the calibration sample with AMP modeling of nearby main-sequence stars observed by TESS, and subgiants observed by *Kepler* and TESS. This work will benefit from the coordinated activities of the Europe-based TASC collaboration, while augmenting their capabilities with cutting-edge modeling techniques.

- **Phase 3:** Recalibrating the convective turnover time with a multivariate Bayesian analysis of extinction-corrected *Gaia* colors and precise spectroscopic parameters. This work will exploit the updated and expanded sample to establish a reliable scale for the stellar Rossby number, which can then be applied to a broader range of systems.

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

3.1 Updating Asteroseismic Properties with Kepler Data

The LEGACY sample consists of 66 solar-type main-sequence stars that were observed by *Kepler* in short-cadence for at least 12 months [23]. For most of these targets, data were obtained almost continuously for more than 3 years—from Quarter 5 (Q5) through the end of the primary mission (Q17). Light curves were extracted from custom pixel masks, corrected for systematics to optimize them for asteroseismology [63], and power density spectra were calculated. For each star, the solar-like oscillations were characterized from the power spectrum using a Bayesian Markov chain Monte Carlo approach, resulting in

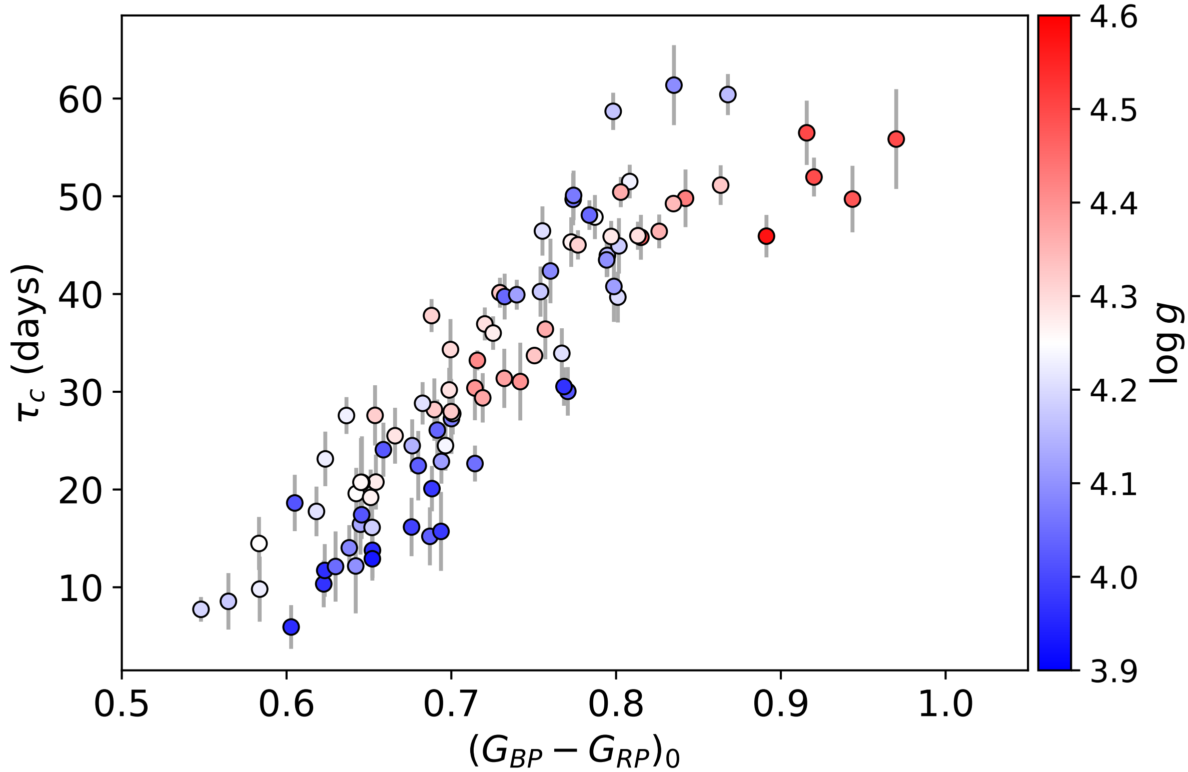

Figure 3: *Convective turnover time calculated from asteroseismic models [4] versus dereddened Gaia color. The extinction correction reduces horizontal scatter, while vertical scatter arises from additional dependencies on spectroscopic parameters. The dependence on surface gravity is evident, with a steeper relation for lower* $\log g$ *(blue) than for higher* $\log g$ *(red).*

mode identifications (ℓ=0–3) for dozens of oscillation frequencies and their corresponding uncertainties. The KOI sample includes 35 suspected and confirmed exoplanet host stars from *Kepler* with solar-like oscillations detected and no minimum requirements on data length or continuity [24]. The data were subjected to the same procedures for light curve preparation and power spectrum analysis as the LEGACY sample, and typically yielded slightly fewer oscillation frequencies due to the lower signal-to-noise ratio (S/N).

The oscillation frequencies for the LEGACY and KOI samples have been used as inputs for asteroseismic modeling, along with spectroscopic parameters and the few precise luminosities that were available before *Gaia* [49, 41]. The asteroseismic properties of the LEGACY sample were used for the initial calibration of τ_c as a function of *Gaia* color [4], but the analysis did not include the KOI sample because the published modeling results did not tabulate the depth of the surface convection zone. We recovered these details from the AMP website for a uniform set of modeling results for the LEGACY and KOI samples, which were obtained with the 2015 version of the AMP pipeline [35, 42]. The resulting estimates of τ_c are shown as a function of extinction-corrected *Gaia* color in **Figure 3**, with the points colored by surface gravity. Compared to the initial calibration sample, the horizontal scatter is reduced by adopting extinction-corrected *Gaia* colors. Furthermore, the vertical scatter appears to be related to spectroscopic parameters, with a clear dependence of slope on surface gravity. *In the first phase of the project, we will use the updated version of AMP to derive precise asteroseismic properties for the LEGACY and KOI samples, adopting spectroscopic parameters from the PASTEL catalog and luminosities from Gaia DR3.*

3.1.1 Spectroscopic Parameters from the PASTEL Catalog

The PASTEL catalog is a compilation of published spectroscopic parameters ($T_{\rm eff}$, [Fe/H], $\log g$) that are based on high-resolution (R>25,000) high-S/N (S/N>50) spectra [64]. It includes FGK stars with $T_{\rm eff}$ between 4000–6500 K, and 80% of the sample has [Fe/H] between −0.5 and +0.5. In the latest update (January 2020), the catalog includes 42,932 parameter determinations for 18,119 unique stars compiled from 1,200 papers. The median errors are 50 K in $T_{\rm eff}$, 0.06 dex in [Fe/H], and 0.1 dex in $\log g$, and the weighted mean parameters for each star in the catalog have been used as a reference sample to assess the systematic errors in several large-scale spectroscopic surveys [65].

Asteroseismic modeling relies on spectroscopic parameters (particularly [Fe/H] and $T_{\rm eff}$) to help break parameter correlations that are intrinsic to stellar models. However, the assessment of a Bayesian likelihood for any given set of model parameters is dominated by the large number of extremely precise oscillation frequencies (typical errors are 1 part in 10,000 for *Kepler* data sets). The role of spectroscopic constraints in the model-fitting is to help distinguish between otherwise comparable matches to the set of observed frequencies. A second role for the spectroscopic parameters (including $\log g$) is to provide observables for the multivariate Bayesian analysis that are independent of the asteroseismic constraints. For example, the stellar surface gravity is strongly constrained by asteroseismic modeling, but adopting a spectroscopic $\log g$ for the multivariate Bayesian analysis ensures consistency with the inputs that are typically available for stars without asteroseismic detections. *We will adopt spectroscopic parameters from the PASTEL catalog for both the asteroseismic modeling and the subsequent multivariate Bayesian analysis.*

3.1.2 Detailed Modeling of Individual Frequencies with AMP

The AMP pipeline originally used models from the Aarhus stellar evolution and pulsation codes [66, 67]. It was released in 2009 [35, 36], and several minor revisions followed as the quality of asteroseismic data from the *Kepler* mission gradually improved [39, 40, 42]. The first major revision was announced in 2023 [20], which coupled the same optimization method to the MESA [68] and GYRE [56] codes. Although most of the input physics in the latest version of AMP were chosen to be the same as in the original version, there were two major updates that addressed the dominant sources of systematic error in the analysis of *Kepler* data sets. First, although the Aarhus models included diffusion and settling of helium [69], the treatment of heavier elements was numerically unstable. The MESA models include diffusion and settling of both helium and heavier elements [70]. Second, the original version of AMP included an empirical correction for inadequate modeling of near-surface layers [71], while the updated version uses a physically-motivated correction that has now become the standard in the field [72]. *We will use the latest version of AMP for updated asteroseismic modeling of the Kepler LEGACY and KOI samples—a computationally intensive task requiring about 2 million CPU-hours in total.*

3.2 Expanding the Calibration Sample with TESS Data

Asteroseismic calibration of the convective turnover time is currently limited to the range of *Gaia* colors represented in the LEGACY and KOI samples ($0.54 < G_{BP} - G_{RP} < 0.97$). Extending the calibration sample to cooler (redder) stars on the main-sequence is challenging, because the amplitudes of solar-like oscillations scale with the ratio of stellar luminosity to mass as $(L/M)^{1.5}$ [73]. The reddest target in the *Kepler* sample is currently the K0 dwarf Kepler-444 [50], but a recent ground-based detection of solar-like oscillations in the K5 dwarf ϵ Ind can immediately extend the *Gaia* color range to $G_{BP} - G_{RP} \sim 1.3$ [74]. The 20-second cadence data from TESS can more effectively sample solar-like oscillations in these cooler main-sequence targets. The elimination of onboard cosmic ray rejection increases the effective integration time by 20%, and the higher Nyquist frequency avoids attenuation of the oscillation signal by 30% or more for stars that are cooler than the Sun [26].

Another way to fill in the calibration sample at redder colors is to extend the analysis to subgiants. Not only do subgiants oscillate with much larger amplitudes than main-sequence stars with the same $T_{\rm eff}$, they also sample lower surface gravities—extending the range of $\log g$ for the calibration. The catalog of solar-like oscillations detected by TESS includes hundreds of cooler subgiants [27], and there are published asteroseismic data sets from *Kepler* and TESS for dozens of subgiants that can be characterized with updated AMP modeling [75, 76]. *In the second phase of the project, we will expand the calibration sample to redder colors and lower surface gravities through AMP modeling of nearby main-sequence stars observed by TESS, and subgiants observed by Kepler and TESS.*

3.2.1 Asteroseismology of Nearby Main-Sequence Stars with TESS

The main-sequence samples from *Kepler* are about 5 magnitudes fainter than TESS asteroseismic targets, with distances up to hundreds of parsecs. The large distances are accompanied by more reddening from interstellar dust, which is what motivates our adoption of extinction-corrected *Gaia* colors. However, the dereddened colors of the *Kepler* targets will necessarily be less precise due to the limited spatial resolution of dust maps near the Galactic plane. By contrast, main-sequence stars with asteroseismic detections from TESS have typical distances in the tens of parsecs, where extinction corrections are generally negligible. Consequently, main-sequence targets from TESS can provide a minimal-extinction reference sample to help validate the extinction-corrected colors of the *Kepler* dwarfs.

Asteroseismic analysis relies on short-cadence (2-minute or 20-second) observations, for which TESS target pixel files and light curves have been delivered to MAST by the Science Processing and Operations Center (SPOC). 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* [77] that has now been adapted for TESS. The yield of asteroseismic detections is much higher from the 20-second cadence data that is available for 956 suitable targets in the extended mission [27]. For main-sequence stars with the highest S/N, *we will fit the power spectra of TESS short-cadence light curves using the Bayesian nested sampling code DIAMONDS [78, 79] to provide individual frequencies for detailed modeling with AMP.*

3.2.2 Solar-like Oscillations in Kepler and TESS Subgiants

As subgiants evolve and the envelope expands, the solar-like (p-mode) oscillation frequencies gradually decrease. Meanwhile, as the star becomes more centrally condensed, buoyancy-driven (g-mode) oscillations in the core shift to higher frequencies. This eventually leads to a range of frequencies where the nonradial oscillation modes can take on a mixed character, behaving like g-modes in the core and p-modes in the envelope ("mixed modes"), with their frequencies shifted as they undergo so-called *avoided crossings* [80, 81]. As with our main-sequence targets, substantial efforts have already gone into the characterization of solar-like oscillations in subgiants from archival *Kepler* data. The largest sample includes 36 subgiants showing clear avoided crossings, selected from the *Kepler* short-cadence targets with observations spanning between 3 months and 3 years [75]. Only stars with high S/N detections and a sufficiently low density of mixed modes were selected, to avoid any ambiguities in the identification of the spherical degree (ℓ=0–3). We add to this sample an additional 8 subgiants observed by *K2* and TESS with published asteroseismic data sets [76].

As an example of the capabilities of AMP for one of the stars in this sample, we can look at results from an analysis of β Hyi. This solar-type subgiant was observed by TESS for 54 days (S67–S68), and a power spectrum of the 20-second cadence light curve shows a clear detection of solar-like oscillations with one avoided crossing. Several teams within TASC attempted to identify the individual oscillation frequencies from this power spectrum, resulting in a list of 23 unambiguous modes. Using these asteroseismic constraints as inputs, along with spectroscopic parameters ($T_{\rm eff}$, [Fe/H]) from the literature [82] and a luminosity derived from the *Gaia* DR3 parallax, AMP determined a precise radius, mass, and convection zone depth ($R_\star = 1.840 \pm 0.032\, R_\odot$, $M_\star = 1.13 \pm 0.05\, M_\odot$, $d_{cz} = 0.290 \pm 0.006\, R_\star$). *We will obtain updated asteroseismic models from AMP for each of the 44 subgiants in our sample with individual frequencies detected by Kepler and TESS.*

3.3 Establishing a Tool for the Stellar Rossby Number

As summarized in section 1, interest in the stellar Rossby number has been reinvigorated by recent observations of the rotational and magnetic evolution of old solar-type stars. The latest analysis of rotation measurements from *Kepler* suggests a critical value of Ro for the onset of weakened magnetic braking near $\mathrm{Ro}/\mathrm{Ro}_\odot = 0.91 \pm 0.03$ [83]. A similar value has been confirmed from direct estimates of the wind braking torque for a small sample of TESS targets [19], by combining inferences of magnetic field geometry from spectropolarimetry, mass-loss rates from X-ray luminosities, measured rotation periods as well as asteroseismic radii and masses (see **Figure 4**). Rossby numbers were calculated from *Gaia* color using the initial asteroseismic calibration [4], normalized to the solar value on this scale. The gray shaded area represents the empirical constraint on $\mathrm{Ro}_{\rm crit}$, and the dotted yellow line shows the evolution of the torque for HD 76151 from a standard spin-down model [84]. There are already indications that Ro may be overestimated for cooler stars like τ Cet, which are expected to remain close to $\mathrm{Ro}_{\rm crit}$ while still on the main-sequence. *In the third phase of the project, we will establish a tool to calculate the stellar Rossby number by recalibrating the convective turnover time with a multivariate Bayesian analysis of extinction-corrected Gaia colors and precise spectroscopic parameters for our updated and expanded sample.*

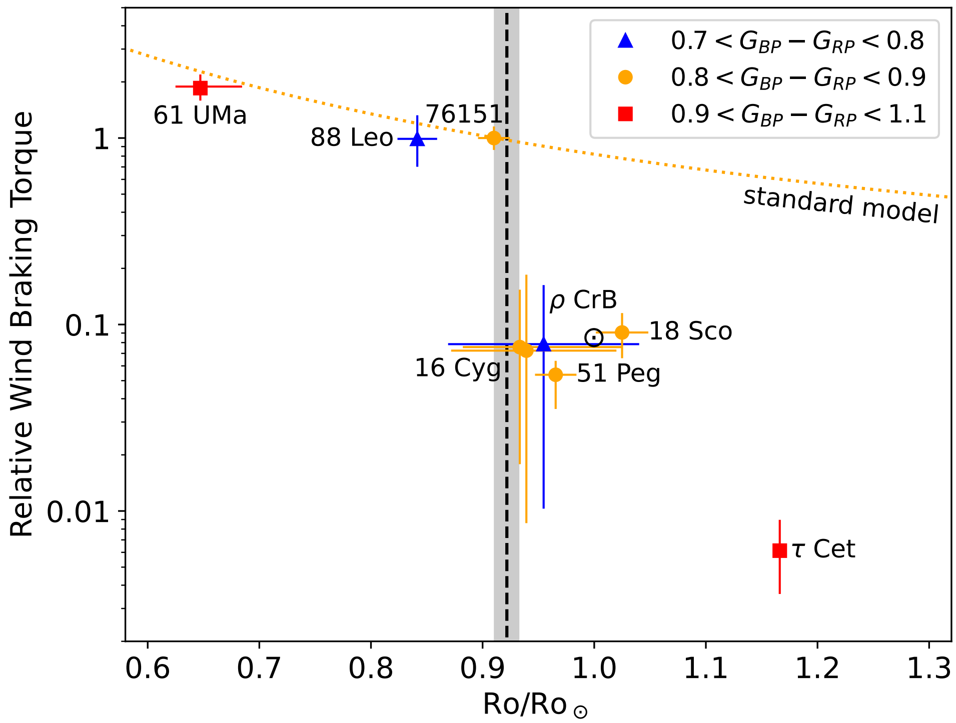

Figure 4: *Estimated wind braking torque relative to HD 76151 as a function of Rossby number normalized to the solar value. Points are grouped by Gaia color, corresponding to solar analogs (yellow circles) and hotter (blue triangles) or cooler stars (red squares). The gray shaded area represents an empirical constraint on the value of Ro for the onset of weakened magnetic braking relative to a standard model of spin-down (yellow dotted line).*

3.3.1 Extinction Corrected Colors from Gaia DR3

The first improvement to our updated calibration of the convective turnover time will be the adoption of extinction-corrected colors from *Gaia*. As noted earlier, this is particularly important for the *Kepler* targets that were used in the initial asteroseismic calibration [4], but it will also be significant for the subgiant samples. For the expanded sample of asteroseismic models that we downloaded from the AMP website (Figure 3), we obtained the extinction correction (`ebpminrp_gspphot`) from *Gaia* DR3. This parameter is subtracted from the $G_{BP} - G_{RP}$ color to "deredden" the effects of interstellar dust, and we found corrections up to 0.08 magnitudes (for the suspected exoplanet system KOI-364). *We will obtain extinction-corrected colors from Gaia DR3 for all of the targets in our expanded sample.*

3.3.2 Multivariate Calibration with Spectroscopic Parameters

Our second improvement to the updated calibration of the convective turnover time will come from a multivariate Bayesian analysis of additional dependencies on spectroscopic parameters from the PASTEL catalog (see section 3.1.1). The initial calibration fit a quadratic relation between τ_c (calculated from asteroseismic models) and the *Gaia* color. The Bayes factor for a quadratic (relative to linear) relation was ∼100, indicating strong evidence for the curvature at redder colors. However, for the sample shown in Figure 3, it appears that the curvature may actually relate to an additional dependence on surface gravity. Indeed, a preliminary analysis of this expanded sample shows additional dependencies on all of the spectroscopic parameters, with [Fe/H] showing the weakest (but still significant) correlation. We considered a multi-linear model, expressed in linearized form as: $\ln \tau_c(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \beta) = \ln \beta + \alpha_1(\mathrm{G_{BP}} - \mathrm{G_{RP}})_0 + \alpha_2 \log g + \alpha_3[\mathrm{Fe/H}] + \alpha_4 \ln T_{\mathrm{eff}}$, where β is a normalization constant and the terms for dereddened color, surface gravity, and metallicity appear on a linear scale because they are already logarithmic quantities. We compared models with only $\alpha_1 \neq 0$ (like the initial calibration) to those with successively more dependencies on spectroscopic parameters. We found that the inclusion of each additional observable leads to many orders of magnitude improvement in the Bayesian evidence, with the most likely model including dependencies on all observables. *We will recalibrate τ_c with a multivariate Bayesian analysis of the updated and expanded sample, and release the resulting calibration as a software tool.*

4 Impact & Relevance

By the end of this project, we will have established a new tool to determine a reliable value of the stellar Rossby number, given only a rotation period, $(\mathrm{G_{BP}} - \mathrm{G_{RP}})_0$ color, and spectroscopic parameters (T_{eff}, [Fe/H], $\log g$). This tool will incorporate the multivariate calibration of the convective turnover time that we establish using the techniques described above. We can immediately apply this tool to the thousands of *Kepler* targets with known rotation periods [12, 85] and spectroscopic parameters measured from the California-Kepler and LAMOST surveys [86, 87], which do not have asteroseismic detections. More generally, the tool will be useful to establish the stellar Rossby number for fainter and cooler main-sequence stars where a rotation period can be measured but asteroseismology is not feasible. We expect a substantial improvement over the initial asteroseismic calibration [4], both from expanding the sample to cover a broader range of *Gaia* color and spectroscopic parameters, and from the multivariate Bayesian analysis. Our timeline is designed to maximize the science return from the TESS mission, but our new tool will also be useful for analyses of additional *Kepler* targets whenever spectroscopic measurements become available.

The research described in this proposal addresses NASA's **Strategic Goal 1**, as defined in the 2022 Strategic Plan: "Expand human knowledge through new scientific discoveries". In particular, it contributes to **Strategic Objective 1.2**: "Understand the Sun, Solar System, and Universe", including two specific goals:

- **Advancing our Understanding of the Sun**: "understand the Sun and its interactions with Earth, the solar system and the interstellar medium, including space weather." (Asteroseismic analysis of *Kepler* and TESS targets will probe the fundamental processes that operate in the Sun under a broader range of physical conditions).
- **Searching for Life Elsewhere**: "habitable planets exist around stars other than the Sun [and] such planets are plentiful. Improving techniques and ideas for discovering and characterizing habitable and/or inhabited environments on these planets [...] will enable prioritization of exoplanets for targeted follow-up observations." (Measuring the evolution of stellar Rossby number 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 a sample of exoplanet host stars using asteroseismology. This is essential to convert precise transit photometry into an absolute radius for the planetary body. In addition, accurate stellar Rossby numbers from our updated asteroseismic calibration will provide important constraints on the space weather environment 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 ACCESS (formerly XSEDE/TeraGrid). More than 14 million CPU-hours of computing time have been allocated to AMP since 2009 for the asteroseismic analysis of *Kepler* and TESS targets, including 1 million CPU-hours awarded in 2023 to support TASC projects. Annual allocation requests are submitted by the AMP administrator each September for time beginning in January, with supplement requests considered every three months.

5.1 Key Milestones

We expect that phase (1/2/3) of this project will require (18/12/6) months to complete. 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:** Compile spectroscopic parameters from the PASTEL catalog, as well as extinction-corrected colors and luminosity constraints from *Gaia* DR3 for the *Kepler* and TESS samples (Q1). Begin updated asteroseismic modeling with AMP (Q1-Q4).
- **Year 2:** Finish updated modeling for the *Kepler* dwarfs, and prepare the results for publication (Q1-Q2). Expand the calibration sample with AMP modeling of existing subgiant data sets from *Kepler* and new subgiant detections from TESS (Q3-Q4).
- **Year 3:** Undertake data analysis and updated AMP modeling for nearby main-sequence stars with asteroseismic detections from TESS (Q1-2). Perform a multivariate Bayesian analysis of the dependence of convective turnover time on extinction-corrected color and spectroscopic parameters (Q3-4). Prepare the results for publication (Q4).

Our experience with the analysis and interpretation of comparable samples of *Kepler* and TESS targets suggests this is a reasonable timeline. These milestones only rely on data that are currently available in the TESS public archive (through S76), with spectroscopic parameters 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#1), will perform the detailed modeling of individual frequencies with AMP, and will participate in the multivariate calibration (with Collaborator#2). The PI will also be responsible for overall project management, and the interpretation, publication, and presentation of results.

- **Collaborator#1:** will coordinate data analysis through the TESS Asteroseismic Science Operations Center (TASOC) for the expanded calibration sample, and will assist in the interpretation, publication, and presentation of results.

- **Collaborator#2:** will coordinate the multivariate calibration of stellar Rossby number from the asteroseismic and spectroscopic properties of the sample, will release a software tool with the final implementation, and will assist in the interpretation, publication, and presentation of results.

5.3 Open Science & Data Management Plan

Data Management Plan: The proposed project, through coordination and collaboration with TASOC, will generate TESS 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 as High-Level Science Products on MAST by the end of the period of performance. The PI 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. A software tool with the final implementation of the multivariate calibration of the stellar Rossby number will be released with documentation on Github by the end of the period of performance. The PI will be responsible for software management.

Open Science Plan: The team 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 asteroseismic stellar properties (radius, mass, luminosity, age, convection zone depth, and convective turnover time) for each star in the expanded sample. These quantities will be archived in the resulting publications using "Data behind the Figure" and "Machine-readable Tables" supplements. The PI will be responsible for ensuring open access publication.

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