

Investigating magnetic dynamo evolution with TESS field dwarfs

Of the measurable properties for a large ensemble of field stars, rotation periods contain the most information about stellar age, and provide the best leverage for advancing our knowledge of galactic archeology as well as exoplanet population demographics via gyrochronology. Angular momentum is carried away through magnetically driven stellar winds, which slows the star’s rotation over cosmic time. This rotation-based ‘clock’ is known as gyrochronology. Cool spots on the star’s surface rotate in-to and out-of view, creating small amplitude ($\pm 1\%$) quasi-periodic changes in the stellar brightness. Using precise light curves available from the *TESS* mission, we expect to measure the rotation periods of around ... stars. For many of these stars it will be possible to infer an age from their rotation periods via gyrochronology.

Some outstanding mysteries regarding the nature of magnetic braking have been revealed, but thus-far unanswered by, *Kepler*. Firstly, a mysterious gap in the rotation period distribution of *Kepler* dwarfs requires either a sharp transition in magnetic dynamo geometry or a gap in the local star formation history as an explanation (McQuillan et al. 2014; Davenport 2017). Secondly, a transitioning magnetic dynamo appears to be responsible for inefficient magnetic braking at old ages in Solar-mass stars. **We propose to help answer these questions by providing a catalog of *TESS* rotation periods for all FFI and CTL stars.** We also intend to use gyrochronology in the cases where it *is* applicable to learn about the evolution of exoplanets across the galaxy.

Scientific Justification The bimodal period distribution among field stars discovered by McQuillan et al. (2013), is shown in Figure 1. Recently, Co-I Davenport discovered this period bimodality extends throughout all masses in the *Kepler* rotation sample for nearby stars (Davenport 2017). This feature could either reflect a drop in the star formation rate around 600 Myr ago or could be explained by a previously unknown variation in the spin-down evolution for low-mass stars. The *TESS* FFI and CTL targets will provide the ideal dataset to test these two scenarios explaining the appearance of a period bimodality. If the bimodal period distribution reflects a discontinuous age distribution, the feature should be local and may disappear at greater distances or along different lines of sight. However, if the bimodality is truly due to a transition point in the spin-down evolution at young ages, there should be little to no variation in the feature with galactic position. We will match the *TESS* FFI and CTL targets to the upcoming data release from the *Gaia* mission (Perryman et al. 2001) to map the rotation period distribution as a function of galactocentric position. With the April 2018 data release from *Gaia* (DR2), we estimate that we will be able to study rotation periods for G dwarfs in the *TESS* FFIs out to ~ 3 kpc.

Although the classical spin-down law of Skumanich (1972): $\text{Period} \propto \text{Age}^{1/2}$ holds for all open clusters with measured periods, it does not appear to describe old field stars (Angus et al. 2015; van Saders et al. 2016). van Saders et al. (2016) found that including a transition to a weakened magnetic braking regime in the gyrochronology models, at a critical Rossby number, provides an improved fit to the data. Further calibration is needed however; a lack of

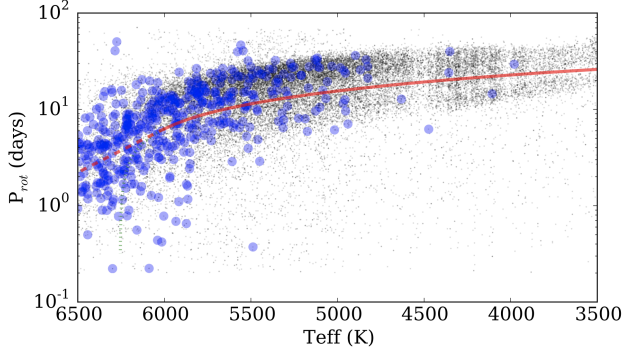


Fig. 1.— From Davenport (2017). Rotation period as a function of effective temperature for the full McQuillan et al., (2014) Kepler sample in black, and the subset of these stars that also feature in the TGAS Gaia DR1 catalogue in blue. Contaminating giants have been removed from the blue sample and the rotation period bimodality is revealed to exist across all temperatures shown. The red line is a 600 Myr rotational isochrone (also known as a gyrochrone).

rotation periods and reliable ages for old and low-mass stars leaves the rotational evolution of stars older than the Sun relatively unexplored. *TESS* will provide thousands of new rotation periods for both FFI and two-minute cadence stars, with the maximum measurable period strongly depending on the length of time it is observed for. Of particular interest are the potentially long rotation periods measurable for stars that fall in the continuous viewing zones. Many of these will have spectra from the *TESS* / *HERMES* survey, from which it will be possible to calculate isochronal ages, enabling further calibration of the gyrochronology relations. We will also use the rotation periods of *TESS* field dwarfs over the whole sky to test the gyrochronology relations using galactic kinematics. Many stars in the *TESS* CTL will have proper motions, parallaxes, positions and radial velocities published in the second *Gaia* data release. These parameters provide the information necessary to calculate galactocentric positions and action angles of the stars, both of which are age indicators. Since one of the few ways to accurately age-date fully convective, late M dwarfs is via kinematics, these new relations will help to infer ages for all stars with $M < 0.35M_{\odot}$, to which gyrochronology cannot be applied.

In addition, we will use the rotation periods of comoving stars identified in the first *Gaia* data release (Oh et al. 2016) to quantify the accuracy and precision of gyrochronology. We have identified 38 stars in 19 pairs with *Gaia* proper motions and radial velocities from *RAVE* that are observable by *TESS*, using *tvguide*. Of these, 34 stars in 17 pairs are already in the CTL list. Because the stars in these pairs are assumed to be recently disrupted binaries, we expect them to have the same age and measuring their rotation periods will therefore provide a test of gyrochronology.

Finally, we hope to use the improved gyrochronology relations, calibrated using *TESS* data to infer the dependence of planet frequency on age and position in the galaxy. *Kepler* revealed tantalizing hints that exoplanets on short orbital periods have larger radii and are more infrequent around young stars (Mann et al. 2017a,b; Rizzuto et al. 2017). Do these trends continue into older ages and do they exist in the field? We will answer these questions by measuring rotation periods for all *TESS* field stars.

Technical Feasibility The extraction of a rotation period from a light curve can be as simple as computing a Lomb-Scargle periodogram or, in cases where the signal is less clear, can be inferred via modeling the correlation between data points. This latter approach could

involve either computing an autocorrelation function (McQuillan et al. 2013), or fitting a Gaussian process to the time series (Angus et al. 2017; Foreman-Mackey et al. 2017b). In cases where signals have long periods and low amplitudes, care is needed to separate real astrophysical signal from instrumental systematics. The measurement of rotation periods is less sensitive to crowding and source confusion than exoplanet transit characterization because the rotation period is not effected by photometric dilution. We will apply two complementary methods to extract and calibrate light curves from the TESS FFIs. First, for bright or isolated targets, we will follow Montet et al. (2017) to estimate aperture shapes and perform aperture photometry for bright sources. Using an ensemble of sources, we will de-trend these light curves using a modified version of *everest* (Luger et al. 2016, 2017) designed to preserve photometric signatures of rotation. This will be achieved by fitting for the systematic effects in the light curve using the *everest* model simultaneously with a Gaussian Process model for the astrophysical variation. Both Aigrain et al. (2016) and Luger et al. (2016) demonstrated that this can preserve stellar variability signals and we will use the *celerite* algorithm (Foreman-Mackey et al. 2017a) to scale the computations to the size of TESS FFI datasets. The precision of existing photometric de-trending methods degrades in crowded fields (for example, Luger et al. 2017). However, to make robust measurements of rotation periods, we do not need absolutely calibrated light curves. Therefore, in crowded fields, we will apply a difference imaging method that was developed for the K2 Campaign 9 microlensing project (Henderson et al. 2016) based on the CPM (Wang et al. 2016) to robustly measure the photometric variations of crowded sources. Unlike standard difference imaging methods, this procedure does not require a reference image. Instead, a causal data-driven model is built to predict the time series in every pixel taking systematic effects into account and the residuals between the observations and the model predictions provide an estimate of the astrophysical variability in each pixel. We will tune this method preserve rotation signals and apply it to detect rotation across the FFIs.

Expected Impact We will provide rotation periods for all two-minute cadence and FFI targets.

Budget Justification PI Angus intends to use the budget to employ a student for 3-4 months. In this time the student will assist in extracting light curves from the FFIs, measuring rotation periods and building a rotation period catalog. The student will also be involved in the scientific project of their choosing: either the rotation period bimodality, gyrochronology of low-mass stars, or gyrochronology of comoving pairs.

References

- Aigrain, S., Parviainen, H., & Pope, B. J. S. 2016, MNRAS, 459, 2408
- Angus, R., Aigrain, S., Foreman-Mackey, D., & McQuillan, A. 2015, MNRAS, 450, 1787
- Angus, R., Morton, T., Aigrain, S., Foreman-Mackey, D., & Rajpaul, V. 2017, ArXiv e-prints, arXiv:1706.05459
- Davenport, J. R. A. 2017, ApJ, 835, 16
- Foreman-Mackey, D., Agol, E., Ambikasaran, S., & Angus, R. 2017a, ArXiv e-prints, arXiv:1703.09710

- Foreman-Mackey, D., Agol, E., Angus, R., & Ambikasaran, S. 2017b, ArXiv e-prints, arXiv:1703.09710
- Henderson, C. B., Poleski, R., Penny, M., et al. 2016, PASP, 128, 124401
- Luger, R., Agol, E., Kruse, E., et al. 2016, AJ, 152, 100
- Luger, R., Kruse, E., Foreman-Mackey, D., Agol, E., & Saunders, N. 2017, ArXiv e-prints, arXiv:1702.05488
- Mann, A. W., Gaidos, E., Vanderburg, A., et al. 2017a, AJ, 153, 64
- Mann, A. W., Vanderburg, A., Rizzuto, A. C., et al. 2017b, ArXiv e-prints, arXiv:1709.10328
- McQuillan, A., Aigrain, S., & Mazeh, T. 2013, MNRAS, 432, 1203
- McQuillan, A., Mazeh, T., & Aigrain, S. 2014, ApJS, 211, 24
- Montet, B. T., Tovar, G., & Foreman-Mackey, D. 2017, ArXiv e-prints, arXiv:1705.07928
- Oh, S., Price-Whelan, A. M., Hogg, D. W., Morton, T. D., & Spergel, D. N. 2016, ArXiv e-prints, arXiv:1612.02440
- Perryman, M. A. C., de Boer, K. S., Gilmore, G., et al. 2001, A&A, 369, 339
- Rizzuto, A. C., Mann, A. W., Vanderburg, A., Kraus, A. L., & Covey, K. R. 2017, ArXiv e-prints, arXiv:1709.09670
- Skumanich, A. 1972, ApJ, 171, 565
- van Saders, J. L., Ceillier, T., Metcalfe, T. S., et al. 2016, Nature, 529, 181
- Wang, D., Hogg, D. W., Foreman-Mackey, D., & Schölkopf, B. 2016, PASP, 128, 094503