Investigating magnetic dynamo evolution with TESS field dwarfs

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1. Introduction

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 though magnetically driven stellar winds, which slows the stars rotation over cosmic time. This rotation-based 'clock' is known as gyrochronology. Cool spots on the stars surface rotate in-to and out-of view, creating small amplitude (± 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. Most of these rotation periods will be convertible into ages as they will be intermediate age FGKM dwarfs.

Some outstanding puzzles regarding the nature of magnetic braking remain to be answered. 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 and the galaxy as a whole.

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2. 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, as shown in Figure 1 (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 age discontinuous age distribution, the feature should be local; it could 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 $\sim$ 3 kpc.

Although the classical spin-down law of Skumanich (1972): Period $\propto$ 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). Asteroseismic pulsators observed by Kepler, older than the Sun, rotate more rapidly than the Skumanich (1972) law predicts they should. van Saders et al. (2016) find 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 rotation periods and reliable ages for old and low-mass stars leaves a question mark hanging over the rotational behaviour of stars older than the Sun. *TESS* will provide rotation periods for old stars that fall in the continuous viewing zones. Many of these stars will have spectra from the *TESS*HERMES survey, from which it will be possible to derive 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. PI Angus is currently using the *Kepler* rotation periods of stars in the first *Gaia* data release to calibrate the relations between rotation period and vertical action dispersion, two tracers of age. Since this relation is likely vary with both galactic longitude and latitude, the rotation periods produced from *TESS* light curves will enable a comprehensive, all-sky calibration of these relations. 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$_\odot$.

In addition, we will use the rotation periods of comoving stars identified in the first *Gaia* data release to quantify the accuracy and precision of gyrochronology.

We will use the rotation periods of planet hosting stars to infer the dependence of planet frequency on age and position in the galaxy. *Kepler* has revealed tantalizing hints that exoplanets on short orbital periods are more infrequent around young stars (**???**). Additionally, there is growing evidence to suggest that younger stars have larger radii. Do these trends continue into older ages and do they exist in the field or is this a cluster-specific phenomenon? We will answer these questions by inferring ages for *TESS* field stars.

2.1. The age distribution of exoplanets

Of particular interest will be the expected ~ 300 gyrochronal ages of exoplanet host stars. The gyrochronal ages of these planet hosts, combined with their isochronal and kinematic ages may allow us to characterize trends in planet properties over time and across the galaxy. Additionally, as rotation both influences and is influenced *by* stellar magnetic fields, it is inextricably related to stellar activity. With so many *TESS* targets being M dwarfs which tend to be particularly active, understanding the magnetic behavior of these stars has never been more important.

The ages of *TESS* stars will also aid galactic archaeology studies, traditionally performed with red giants, although greater distances can be reached with red giants, main sequence stars are far more numerous.

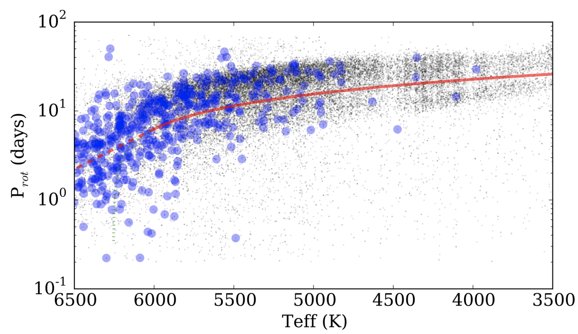

Fig. 1.— From Davenport (2017). Rotation period as a function of effective temperature for the full McQuillan et al., (2014) Kepler sample in black, and the subset of these stars that also feature in the TGAS Gaia DR1 catalogue in blue. Contaminating giants have been removed from the blue sample and 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).

3. Analysis plan

4. Technical Feasibility

4.1. Measuring Rotation Periods

In this era of large photometric surveys (Kepler/K2, TESS, WFIRST, LSST, PTF, PanStarrs and more) rotation periods are quickly becoming one of the most accessible properties of stars. Precise light curves produced by these surveys often reveal the presence of dark spots on the surfaces of cool stars which revolve with the stellar surface creating an overall dimming effect once every rotation period. Dark spotted regions and bright faculae leave a characteristic trace in the light curve from which a rotation period can be inferred. The extraction of a rotation period from a light curve can be as straight-forward as computing a Lomb-Scargle periodogram or, in cases where the signal is less clear, can be inferred via modelling 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., 2017). Signals produced by the rotation of spotted stars can have amplitudes of a few percent of the total flux, but can also have very low amplitudes of a few parts per million. The frequencies of high amplitude signals are easy to measure and, in these cases, most measured frequencies will agree regardless of the technique used to measure them. Similarly, short-period signals are easy to measure, especially if light curve variations are sinusoidal in shape. In the low amplitude and long period cases however, 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. 2017) 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.

5. Expected Impact

We will provide light curves and rotation periods for both the two-minute cadence and FFI targets.

6. 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.

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