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 though 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% or less) quasi-periodic changes in the stellar brightness from which a rotation period can be measured. Thousands of photometric rotation periods have been measured from *Kepler* and *K2* light curves this way, but these surveys focused on small areas of the sky whereas *TESS* will open unexplored parts of the galaxy to rotational evolution studies. Some outstanding mysteries regarding the nature of magnetic braking were 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 (van Saders et al. 2016). To shed light on this behavior **we propose to provide a catalog of $\sim$ 1 million rotation periods for *TESS* Full Frame Image (FFI) stars, to map the rotation period bimodality as a function of galactic position and to calibrate gyrochronology using *TESS–HERMES* spectra, *Gaia* kinematics and *Gaia* comoving pairs.**

<u>**Scientific Justification**</u> The bimodal period distribution among field stars discovered by McQuillan et al. (2013), is shown in Figure 1. Recently, Co-I Davenport found 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 targets will provide the ideal dataset to test these two scenarios. If the period bimodality 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 targets to the upcoming second data release from the Gaia mission (Perryman et al. 2001) to map the rotation period distribution as a function of galactic position. Outside the Continuous Viewing Zone (CVZ) we will focus on F and G stars since the 27.4 day baseline of *TESS* fields will limit measurable rotation periods to less than around 15 days. The longer time coverage in the CVZ will allow us to study the rotation period bimodality in K and M dwarfs too, since the bimodality appears at longer rotation periods for these lower mass stars. Unlike *Kepler* and *K2* light curves, *TESS* **provides the all-sky coverage necessary to map the period bimodality across the galaxy.**

Although the classical spin-down law of Skumanich (1972) (Period $\propto$ Age$^{1/2}$) holds for all

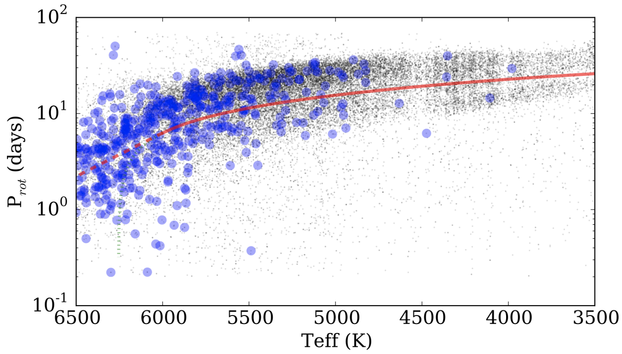

Fig. 1.— From Davenport (2017). Rotation period as a function of effective temperature for the full McQuillan et al., (2014) *Kepler* sample in black, and the subset of these stars that also feature in the TGAS Gaia DR1 catalogue in blue. Contaminating giants have been removed from the blue sample and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

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 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 *long* rotation periods for stars that fall in the CVZ. 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 propose to calibrate gyrochronology at old ages for FGKM stars using the isochronal ages of *TESS–HERMES* stars.** We will also use the rotation periods of *TESS* field dwarfs over the whole sky to test the gyrochronology relations using galactic kinematics. Many *TESS* FFI targets 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-angle coordinates of the stars, both of which are age indicators. **We propose to calibrate the gyrochronology relations at old ages for FGKM stars using vertical actions of *Gaia* DR2 targets.** 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 $M < 0.35 M_{\odot}$, to which gyrochronology cannot be applied.

Oh et al. (2016) identified over 10,000 comoving pairs of stars using proper motions from the first *Gaia* data release. Of these, 8 dwarfs and subgiants in 4 pairs have *RAVE* radial velocities consistent with being comoving and are already in the Candidate Target List. Following Campante et al. (2016) we calculate that these stars have oscillation detection probabilities greater than 0.85, based on their *RAVE*-on $T_{\rm eff}$, $\log g$ and radii (Casey et al. 2017) and their observation baseline, from `tvguide`. Since these stars would make interesting targets for both asteroseismology and exoplanet search, we include a list with this proposal. The stars in these pairs are likely recently disrupted binaries so we expect them to have similar ages and measuring their rotation periods will therefore provide a test of gyrochronology. An additional 5000 bright comoving pair candidates lie in the southern ecliptic hemisphere and will be ideal FFI targets for gyrochronology studies. **We will use the rotation periods of comoving stars to quantify the accuracy and precision of**

gyrochronology.

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 (*e.g.* McQuillan et al. 2013), or fitting a Gaussian process to the time series (Angus et al. 2017; Foreman-Mackey et al. 2017). 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. 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 to preserve rotation signals and apply it to detect rotation across the FFIs.

Based on Sullivan et al. (2015), we expect around 10 million *TESS* FFI targets brighter than 15th magnitude in the southern ecliptic hemisphere. We intend to prioritize certain groups of stars for period analysis, calculating a simple (and computationally fast) Lomb-Scargle periodogram for the low priority objects and running a full probabilistic, Gaussian process period analysis on the high priority targets. High priority targets will include: comoving pairs, stars in the CVZ (especially those with spectra), stars in TGAS, stars at large distances, plus potential asteroseismic dwarfs and exoplanet hosts. The number of high priority targets with probabilistic rotation periods will be limited by computation power, but we conservatively estimate that we can produce full rotation period posterior PDFs for $\sim$ 30,000 stars. Based on the expected photometric precision of *TESS* (Sullivan et al. 2015), we expect to be able to measure rotation periods for FFI stars down to 15th magnitude. We note however that not all stars will have measurable rotation periods: even if they are bright enough not all stars show rotational variability in their light curves either because they are pole-on or inactive. We will vet incorrect rotation period measurements using a combination of a Lomb-Scargle periodogram and an autocorrelation function by training on a set of light curves with a range of variability amplitudes and known periods. Based on the fraction of stars with measurable rotation periods in McQuillan et al. (2014), and the more restrictive baseline of *TESS* relative to *Kepler*, we predict that the final catalog will contain around one million rotation periods.

We have already begun to construct a rotation period catalog of *K2* stars, for which we have received funding from the Archival Data Analysis Program (ADAP). Figure 2 shows a map of preliminary rotation periods for one of four *K2* fields processed so far.

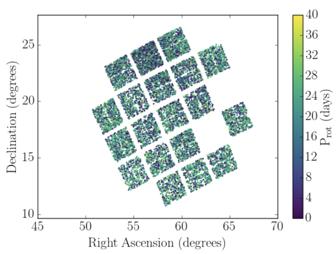

Fig. 2.— All stars observed during K2 campaign 4, plotted according to their equatorial coordinates and colored by their preliminary rotation period. These rotation periods were measured using a simple ACF method, applied to everest (Luger et al., 2015) light curves.

Expected Impact We will provide rotation period posterior probability density functions and best fit estimates for $\sim$ 30,000 high priority FFI targets rotation periods and point estimates for $\sim$ 1 million lower priority FFI stars using a combination of Lomb-Scargle periodogram and autocorrelation techniques. We will release an open source python package for measuring rotation periods of *TESS* FFI targets plus code for inferring stellar ages from rotation periods, based on a new gyrochronology relation calibrated using *TESS*– *HERMES* spectra, *Gaia* kinematics and comoving pairs.

Budget Justification PI Angus will employ two undergraduate students for 3-4 months who will assist in extracting light curves from the *TESS* FFIs and building a rotation period catalog. These students will also be involved in the scientific project of their choosing: either the rotation period bimodality, gyrochronology of FGKM stars, or gyrochronology of comoving pairs. The remaining budget will be used for bringing all Co-Is together in order to make and execute analysis plans and for presenting the results at conferences.

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