Investigating magnetic dynamo evolution with TESS field dwarfs

R. Angus[1] J. R. Davenport[3] D. Foreman-Mackey[6], S. Oh[8], D. Busazi[5], A. Mann[1] D. Kipping[1]

1. Introduction

Age is a fundamental stellar parameter of great interest to at galactic archaeologists and exoplaneteers alike but unfortunately it is a difficult attribute to measure for main sequence F, G, K, and M stars in the field. 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 ($\pm$ 1%) quasi-periodic changes in the stellar brightness. While rotation periods have previously been measured from starspot-induced flux modulations for hundreds of stars from the ground, space-based photometric surveys have opened the door to homogeneous ensemble measures of stellar rotation, and therefore age. Using precise light curves available from the TESS mission, we expect to measure the rotation periods of around ... stars. Many of these rotation periods will be convertible into ages as they will be intermediate age FGK and early M dwarfs. 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 will allow us to characterize trends in planet properties over time and across the galaxy.

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[1]Department of Astronomy, Columbia University, New York, NY

[2]Simons Fellow, RuthAngus@gmail.com

[3]Western Washington University, Bellingham, WA

[4]NSF Fellow

[5]Florida Gulf Coast University, Fort Myers, FL

[6]Center for Computational Astronomy, Flatiron Institute, New York, NY

[7]Hubble Fellow

[8]Princeton University, Princeton, NJ

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.

We propose to: 1. Measure accurate rotation periods for every available TESS FFI and two-minute cadence target. 2. Determine the origin of the mysterious rotation period bimodality discovered with Kepler by tracing the rotation period distribution over the whole sky, and out to further distances utilizing public Gaia data. 3. Measure the star formation history across the sky using a new Bayesian age-dating system. 4. Further characterize the intrinsic uncertainty in gyrochronology ages using comoving pairs identified in the first Gaia data release. 5. Infer the distribution of exoplanets as a function of time and galactic position.

2. Scientific Justification

2.1. Rotation period bimodality

One of the most remarkable results from the Kepler rotation period catalog was the discovery of a bimodal period distribution among field stars by McQuillan et al. (2013), which is shown in Figure 1. The bimodality separats M dwarfs into two populations, those with rotation periods longer than ~ 20 days, and those with periods between ~ 1 and 20 days. Follow-up analysis of the Kepler data by McQuillan et al. (2014) found the period bimodality extended to include K dwarfs. 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). Two scenarios have been proposed to explain the observed period bimodality. In the first scenario, initially proposed by McQuillan et al. (2013), the rotation period distribution reflects the local star formation history, and thus the bimodality represents a drop in the star formation rate around 600 Myr ago. This model is supported by both the extension of the bimodality to earlier spectral types by Davenport (2017), and also the tentative evidence for two distinct proper motion distributions. However, such a variation in the star formation rate on short timescales is in tension with independent observational efforts to determine the local star formation history. While colormagnitude diagram inversions from Hipparcos have suggested a similarly short timescale variation in star formation of ~ 0.5 Gyr (Hernandez et al. 2000), other studies find slower variations over several Gyr (*e.g.* Cignoni et al. 2006). Using white dwarf cooling models to infer the local formation history (cosmochronology) also supports higher star formation several Gyr ago, but can rarely achieve age resolution better than ~ 1 Gyr due to small sample sizes (Tremblay et al. 2014). The spatial extent of such coherent and localized variations in star formation history is unknown. The second scenario explaining this feature is a previously unknown variation in the spin-down evolution for low-mass stars. In this model, the star formation history would be continuous over the past ~ 1 Gyr, and around 600 Myr stars would move quickly through the observed period minima due to some phase transition or feedback mechanism. While this model is not predicted by angular momentum loss prescriptions, rapid transitions in rotation period are observed for stars in young clusters. Stars move quickly from the rapidly rotating convective sequence (periods of $\sim< 1$ day) to the interface sequence (periods of several days) during the first few hundred Myr, with lower mass stars taking longer to make this transition as they settle onto the main sequence (Barnes 2003). Secondly, a gap in chromospheric activity levels for solar-type field stars has also been observed (Vaughan & Preston 1980). While this magnetic activity indicator smoothly varies with stellar ages over long timescales, the gap indicates a rapid transition phase from active to inactive is present within the first Gyr (Pace et al. 2009). Thirdly, the angular momentum loss underpinning gyrochronology seems to slow for stars older than the Sun, indicating a potential change in the magnetic dynamo for slower rotators (Angus et al. 2015; van Saders et al. 2016).

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.

To map the rotation period distribution as a function of galactocentric position we will match the TESS FFI and CTL targets to the upcoming data release from the Gaia mission (Perryman et al. 2001). This will also allow us to remove contaminating subgiants and binary stars from the sample, leaving only single main sequence stars. 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.

2.2. Gyrochronology

Gyrochronology is by far the most widely applicable, relatively precise age-dating method available. Although the phenomenon of magnetic braking has been closely studied since its discovery in the mid/late 20th century, the manifestations of magnetic fields and their effects on rotation and activity are complex; the physics underpinning rotational evolution are far from well-understood. 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. Once a star reaches a critical Rossby number (the ratio of the rotation period to the convective overturn time), magnetic braking efficiency effectively drops to zero. This means a 5 Gyr star of Solar mass will have the same rotation period as a 6 Gyr and rotation period cannot be used as an age proxy. The transition occurs at around Solar age for Solar mass stars but later for less massive stars and earlier for more massive stars. 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.

We will use the rotation periods of TESS field dwarfs to test the gyrochronology relations using galactic kinematics. Many stars in the TESS CTL will also have proper motions, parallaxes, positions and radial velocities published in the second *Gaia* data release. These parameters provide the information necessary to calculate both galactocentric positions and action angles of the stars, both of which are age indicators. Vertical action (angular momentum through the plane of the Milky Way) increases over time due to orbital heating and has been demonstrated to increase with age (*e.g.* **?**). Galactocentric position can also determine a star's age, since different stellar populations, thin or thick disk, halo and bulge have different average ages. 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$_\odot$.

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

Although this effect reduces the applicability of gyrochronology for stars more massive than the Sun, in practise, for Solar masses and below, down to $0.35M_\odot$, gyrochronology can still be considered an effective dating method.

We will use the rotation periods of planet hosting stars to infer the age-

dependence of planet frequency.j Kepler alone has not yet produced a sufficient number of stars with rotation periods to reliably characterise the time-dependent frequency of exoplanets. Mann et al. (2016a), Mann et al. (2016b) and Rizzuto et al. (2017) detected transiting exoplanets in four young open clusters observed by the K2 mission.

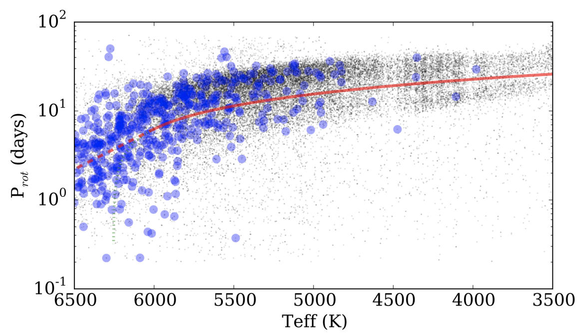

Fig. 1.— From Davenport (2017). Rotation period as a function of effective temperature for the full McQuillan et al., (2014) Kepler sample in black, and the subset of these stars that also feature in the TGAS Gaia DR1 catalogue in blue. Contaminating giants have been removed from the blue sample and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

We intend to measure rotation periods for all mid to low-mass dwarfs that show evidence of rotational modulation in their light curves.

Need to measure rotation periods of all stars if you want to infer the distribution of planets as a function of age.

It looks like hotter stars stop spinning down at around the age of the Sun. However, that does not necessarily mean that gyrochronology cannot be used to infer ages. Gyro works for low mass stars down to around 0.35 $M_{\odot}$ (CITATION), up to the age of the Universe. It works for Solar-mass stars up to the age of the Sun and for stars more massive than the Sun (but less massive than the Kraft break) it works to gradually decreasing ages. This means that X% of stars in the TIC are likely to have ages that can be determined by gyrochronology.

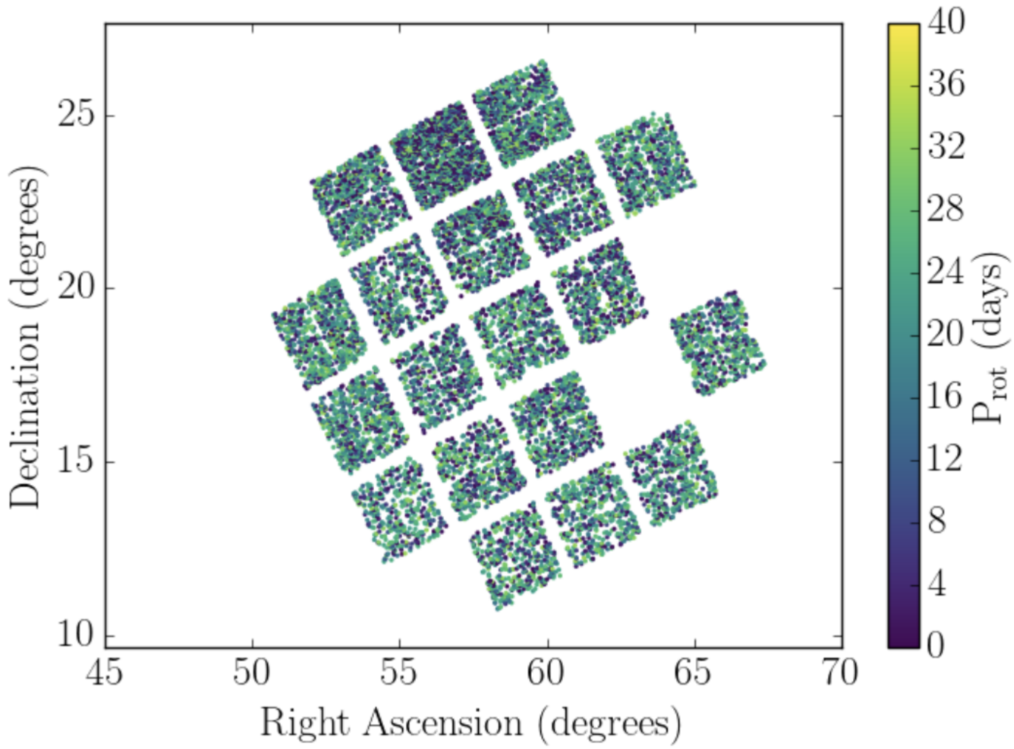

Fig. 2.— All stars observed during K2 campaign 4, plotted according to their equatorial coordinates and colored by their preliminary rotation period. These rotation periods were measured using a simple ACF method, applied to everest (Luger et al., 2015) light curves.

4. Expected Impact

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

5. 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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