Scientific/Technical/Management

1 Introduction

Among the key observational properties of main sequence stars in our galaxy, age is the most difficult to determine. Traditionally, fitting isochrones to cluster stars was one of the only precise methods for measuring ages, and was impossible for the majority of isolated field stars. Methods such as asteroseismology and measuring Li abundances require time intensive observations for each target and are not capable of producing the large quantity of ages needed for exoplanet and galactic population studies. To improve our understanding of star and planet formation and evolution, as well as the history of the Milky Way, we must be able to constrain the ages of low-mass stars like the Sun in the galactic field.

Fortunately nature has provided a power means to determine ages for main sequence stars via their rotation. 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 ($\sim$1%) quasi-periodic changes in the stellar brightness. While rotation periods have previously been laboriously measured from starspot-induced flux modulations for hundreds of stars, space-based photometric surveys have opened the door to homogeneous ensemble measures of stellar rotation, and therefore age. **With the precise, long-duration light curves available from the *Kepler*/K2 mission, we can determine the rotation periods and ages for nearly 100,000 main sequence field stars.**

The *Kepler* mission broke new ground by producing rotation periods for tens-of-thousands of field stars within a single $\sim$110 sq deg field of view, and discovered a surprising bimodal distribution of rotation periods. Two competing explanations have arisen for this mysterious feature: a bimodal age distribution for nearby stars, or a new subtlety in stellar angular-momentum-loss mechanisms. Detailed calibrations of gyrochronology models with the *Kepler* rotation sample also revealed the need for samples of stars with a wider range of ages and compositions. Fortunately the ongoing *Kepler* extended mission, K2, has currently produced light curves from 14 additional fields throughout the Galaxy.

To enable studies of stellar ages from rotation periods with K2, we propose to:

1. Measure accurate rotation periods for every available K2 target, using new statistical methods we have developed to cope with significant instrumental systematics in the K2 data. This value-added dataset will improve the *Kepler* data legacy for field stars, and provide a critical training set for the TESS mission.

2. Produce updated gyrochronology relations based on a wider range of field star ages, and additional open clusters within the K2 fields.

3. Determine the origin of the mysterious rotation period bimodality discoverd with *Kepler* by tracing the rotation period distribution in each K2 field, and out to further distances utilizing public Gaia data.

4. Measure the star formation history within each K2 field using a new Bayesian age-dating system.

2 Scientific Motivation

Galactic archaeology and exoplanet populations are two rapidly accelerating fields of interest within astronomy. Although seemingly unconnected, these two fields are linked by a mutual requirement for precise stellar parameters. To galactic archaeologists, ages and elemental abundances are the most important parameters. Indeed, most galactic archaeology surveys target exactly these properties. For exoplaneteers, masses and radii have historically been the most important stellar parameters for understanding planetary systems. With a growing number of planet hosts with precise masses and radii, attention is turning toward other parameters such as ages to under the history and evolution of these systems. Age is therefore a fundamental stellar parameter of great interest to two large communities of astronomers. However it is a difficult attribute to measure for main sequence F, G, K, and M stars in the field, in part because low-mass dwarfs do not move far on the Color-Magnitude diagram (CMD) during their hydrogen burning lifetimes. Further, competing stellar evolution models predict different ages for the same star. Of all the measurable properties for a large numbers of 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.

2.1 Age-Dating Field Stars with Rotation

The seminal work of Skumanich (1972) laid the foundation for our model of the stellar age–rotation–activity relationship. When stars settle onto the main sequence they may have a range of initial rotation periods based on the angular momentum available in their primordial environment. However, rotation velocities converge by a few 100 Myr (for Solar-type stars), and then follow a standard spin-down evolution (Barnes, 2010). Stars continuously lose angular momentum due to magnetically driven winds. Stellar rotation also drives the internal magnetic dynamo, resulting in decreasing surface magnetic activity as the star slows (rotation period increases). Older, slower rotating stars therefore have smaller starspots, making the detection rotation more difficult as stars age. Deriving ages for field stars therefore requires knowing their color (as a proxy for stellar temperature or mass) and their surface rotation period (Barnes, 2007), and can produce ages with errors as low as $\sim$10% (Barnes, 2010).

The rate of this angular momentum loss has historically been calibrated using main sequence stars at a range of masses in stellar clusters with known ages, leading to a useful clock called "gyrochronology" (Barnes, 2003). Several gyrochronology model (or gyrochrones) parameterizations exist, each using various age benchmarks for calibration. Nearly all gyrochronology models suffer from lack of constraint at older ages; often the Sun is the only benchmark used older than $\sim$1 Gyr since accessible nearby open clusters are typically young ($<$ 600 Myr).

In Figure 1 we demonstrate the subtle differences between competing gyrochronology models for Solar mass stars. To increase the available sample of calibration sources available at Gyr ages, Co-I Angus has produced improved gyrochronology models using *Kepler* asteroseismic targets (Angus et al., 2015). Note: the additional calibration sources at Solar

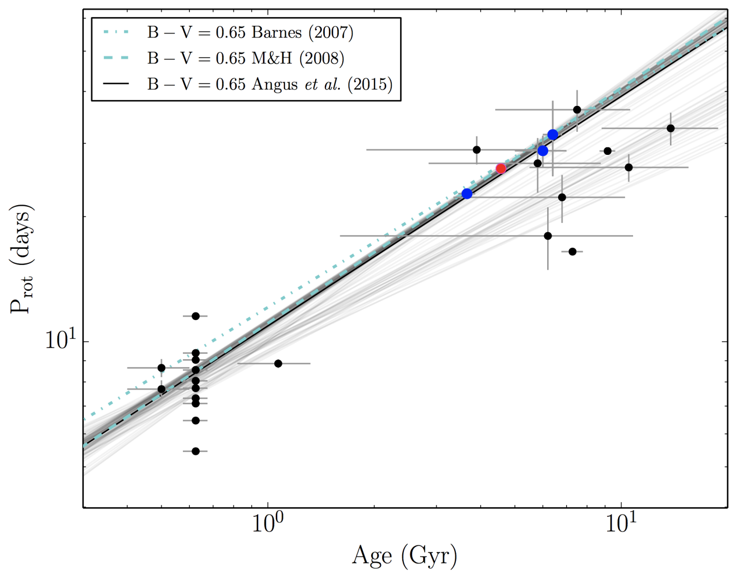


Figure 1: Figure 6 from Angus et al. (2015), showing an improved gyrochronology relation calibrated using *Kepler* asteroseismic targets (black dots) and the Sun (red dot), compared with other standard gyrochronology models (blue dashed and dotted lines).

ages means the Angus model is not forced to exactly fit the Sun's rotation period, as other traditional models do. Unfortunately, asteroseismology cannot yet provide ages for stars with masses much lower than the Sun. *Kepler* rotation period samples have demonstrated that magnetic braking may become less efficient at older ages (van Saders et al., 2016). The Angus et al. (2015) gyrochronology study also found that cluster and asterosismic field star targets may not follow the same spin-down model, possibly indicating bias in the dynamical histories of these samples. Additional calibration sources are desperately needed for stars older than the Sun, and for lower-mass dwarfs.

2.2 Rotation Periods from *Kepler* and K2

Previous ground-based efforts to constrain stellar rotation periods for single, isolated field stars have resulted in few measurements. Detecting rotation from Doppler line broadening requires obtaining medium- to high-resolution spectroscopy of individual targets, and can be subject systematic effects such as from limb darkening approximations (Collins & Truax, 1995). These observations also require time on larger aperture telescopes to reach fainter magnitudes needed to study rotation from low-mass field stars, or for studying the entire mass range within stellar clusters. Ground-based photometric wide-field surveys overcome many of the difficulties in gather large samples of field stars or entire stellar clusters. However, long duration monitoring with relatively high cadence and high photometric precision is required to detect the small amplitude and slowly varying flux modulations from starspots. These campaigns typically yielded rotation samples of hundreds to ∼1000 stars (e.g. Hartman et al., 2010, 2011)

Space-based photometry surveys designed for exoplanet transit searches such as *Kepler* (Borucki et al., 2010) have produced a revolution in stellar rotation studies. The original *Kepler* mission produced light curves up to four years in duration with ∼100 ppm precision at 30-minute cadence for more than 200,000 stars. From this remarkable dataset, more than 30,000 unique stellar rotation periods have been measured using a variety of time series analysis techniques such as the Lomb-Scargle Periodogram (Reinhold et al., 2013) and the Autocorrelation Function (McQuillan et al., 2014). This bounty of rotation periods has also allowed the first ensemble investigations in to stellar surface differential rotation (e.g. Reinhold et al., 2013), revealed stars with near solid-body rotation (Davenport et al., 2015), and highlighted the many degeneracies in disentangling starspot evolution and differential rotation (Aigrain et al., 2015).

After hardware failures made observations of the original field impossible, an extended *Kepler* mission was designed to observe many fields with ∼3 month durations. The K2 mission has observed fields spaced along the ecliptic plane, ranging from low galactic latitudes that include multiple open clusters, to high galactic latitudes that include many older field stars (Howell et al., 2014). The K2 fields also include several benchmark stellar clusters including the Solar-age M67, the Pleiades and Hyades, and M35. To date K2 has released data from 10 distinct campaigns (or fields), including more than 252,000 targets, exceeding the original *Kepler* mission. An additional 6 campaigns are currently scheduled. Importantly, K2 data quality has been demonstrated to approach that of the original *Kepler* mission (Luger et al., 2016), and has been successfully used to measure rotation periods for select targets such as open cluster stars (e.g. Douglas et al., 2017).

K2 provides the ideal dataset to both extend the *Kepler* studies of field star age distributions, and to amass a sample of better calibration sources for gyrochronology models. The range of K2 fields positions within the Galaxy means the sample spans a much wider variety of stellar ages for more distant stars ($\gtrsim$1pc), and provides multiple opportunities to constrain the local star formation history for nearby stars. This makes the gyrochronology study of field stars with K2 an unique and valuable comparison to complimentary efforts in studying galactic archeology using chemical abundances, such as with APOGEE (Hayden et al., 2014). Producing rotation periods for these older stars, and the additional open clusters including the benchmark Solar age M67 available in the K2 data, will also lead to new gyrochronology relations, and to test the universality of the age–rotation–activity relation put into question by Angus et al. (2015).

2.3 A Mysterious Period Bimodality

Then this weird thing appeared, which is an open mystery - a bimodal period distribution - whoa (McQuillan et al., 2013). this was then extended to higher masses by Davenport (2017). Explanations are either a break from single spin-down law (possibly from different initial periods, or some new physics maybe due to chemical abundances) or represents an age bimodality of local stars.

Since this effect is seen only within 300pc so far (and only within Kepler data) due to sample properties, cannot be sure what spatial or compositional dependence this has, need a sample that spans a wider spatial area and more ages of stars

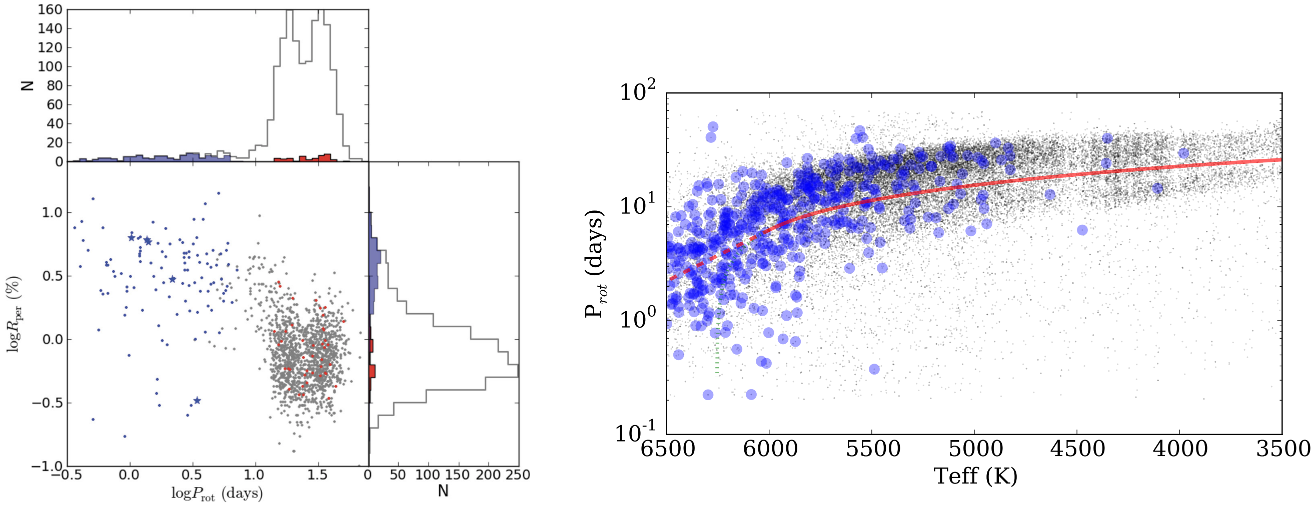


Figure 2: Left – Figure 9 from McQuillan et al. (2013); the discovery of a bimodality in rotation periods from *Kepler* M dwarfs (middle panel). Right – Figure 3 from Davenport (2017), showing all *Kepler* rotation periods from McQuillan et al. (2014) (black dots), and main sequence stars with Gaia DR1 distances. The bimodality discovered for M dwarfs extends to G and K stars, and straddles a 600 Myr "gyrochrone" (red line).

3 Proposed Research

3.1 Measuring Rotation from K2 Using the Systematics-Insensitive Periodogram

we propose the first systematic study of stellar rotation periods from the K2 data.

this will include ∼XXXXX stars from Campaigns 0-16. This includes data for multiple stellar clusters that were taken as part of the Guest Observer program.

data will be reduced using SOME FLAVOR of K2 pipeline.

the Angus et al. (2016b) rotation period pipeline will then be applied to every light curve. we will generate and save every periodogram for potential follow-up analysis of differential rotation and multi-period systems

spurious signals from transits and flares will be filtered out (some smoothing or high-freq removed in the SIP?)

for stars with good period recovery, fourier fits will identify eclipsing binaries and pulsating systems (or something like this)

The *Kepler* rotation period catalog from McQuillan et al. (2014) found a yield of $\sim 25\%$ of stars had measurable rotation periods using the Autocorrelation Function. From our

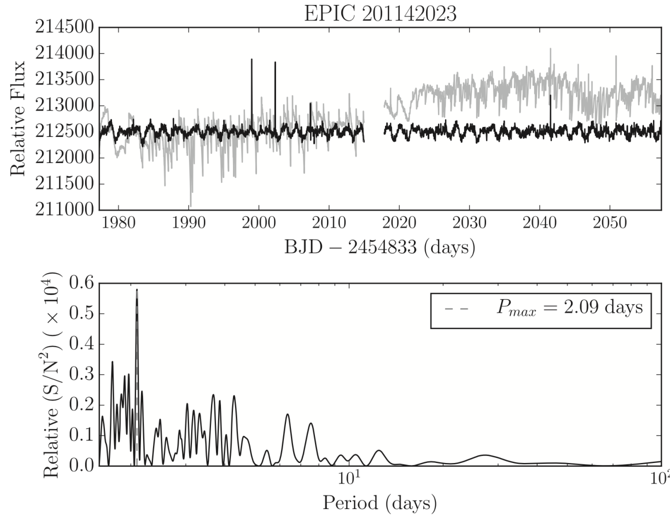


Figure 3: figure 6 from Angus et al. (2016b), showing the processing of the light curve and resulting SIPeriodogram. more simple methods give erroneous periods for this object of either 3 days via ACF, or 59 days via normal Lomb-Scargle methods.

sample of 252,000 available K2 targets, we expect to recover ∼63,000 new rotation periods, bringing the total *Kepler*/K2 sample to ∼100,000.

3.2 Exploring the Period Bimodality

by combining our sample with the distances provided in the forthcoming Gaia DR2 catalog, we will be able to extend the methodology of Davenport (2017) to filter our subgiants and binary stars for our entire sample.

we then can make 3d exploration of period distribution, to see if the bimodality exists for all field stars near the sun.

the big goal here is to decide which explanation is correct!

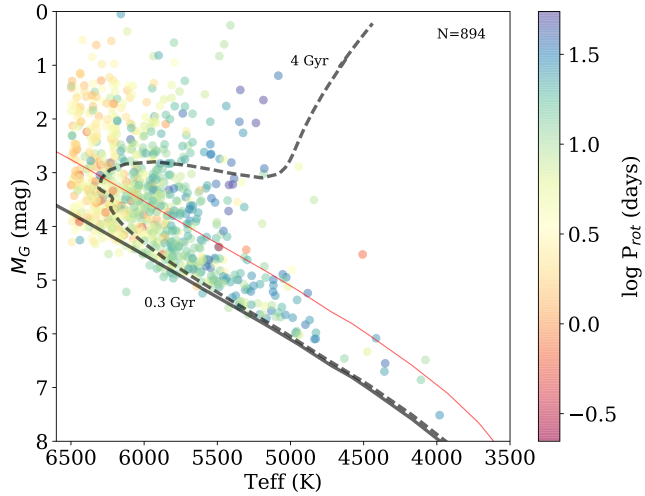
3.3 Mapping Ages in each Field

our catalog of rotation periods from K2, combined with existing catalogs from Kepler, we will have the largest set of rotation periods ever to use for population analysis. using new technique being developed by Ruth (Chronometer) we will have improved age estimate for every star based on single rotation values. then we combine this to get age distribution within each K2 field.

Demonstration figure?

discussion of improved gyrochronology calibration?

this is partially an extension of the period bimodality work (if it's an age effect), but to create a detailed map of the ages of these field stars at a range of galactic latitudes in the 17 pencil-beams available from K2. combining with the periods from Kepler, will be even



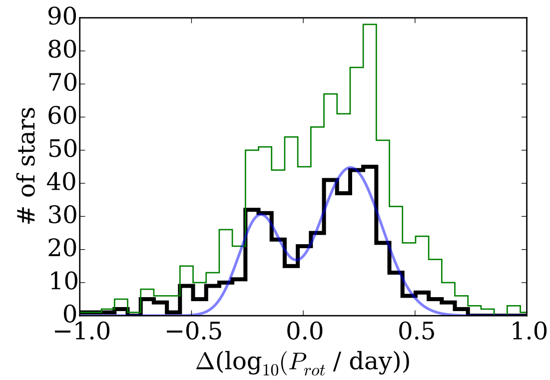


Figure 4: Left – Figure 2 from Davenport (2017), showing the absolute Gaia magnitude versus temperature for *Kepler* stars with known rotation periods in the Gaia DR1 catalog. Sub-giant stars can be separated from main sequence targets using isochrone models (black solid & dashed lines). Right – Figure 4 from Davenport (2017), showing the rotation period distribution relative to a 600 Myr "gyrochrone" before (green line) and after (black line) filtering our sub-giants. The bimodal distribution is apparent, and fit with a 2-Gaussian model (blue line).

better. ultimately we'd like to compare to the age distributions in simulations of these fields from TRILEGAL, and from other age indicators (asteroseismology, flare ages, etc)

4 Team Qualifications

PI Davenport has used *Kepler* to conduct the largest survey to-date of stellar activity from flares, as well as multiple investigations of starspots and their evolution with time using *Kepler* data. From these studies, Davenport has developed an age model for flare activity that will be directly comparable to the ages and starspot amplitudes derived from this study. He has also recently discovered the rotation period bimodality first noted with *Kepler* M dwarfs by McQuillan et al. (2013) extends to G and K dwarf stars (Davenport, 2017). Davenport previously collaborated on NASA ADP grant NNX09AC77G to characterize NIR variability using the 2MASS Calibration Scan Point Source Working Database (Davenport et al., 2012, 2015). He has mentored numerous students on projects using *Kepler* data, resulting in student-led publications such as the flare activity of a unique M dwarf binary system GJ 1245AB (Lurie et al., 2015), and exploring the poorly understood origins of wide binary stars through stellar rotation (R. Clarke in prep). He will manage the overall project, and lead the investigation and publication of the period bimodality exploration.

Co-I Angus is an expert in the extraction of periodic signals from *Kepler* data using

Gaussian Processes (Angus et al., 2016a) and other cutting-edge statistical techniques. She is the author of tools for generating Systematics-Insensitive Periodograms for both *Kepler* and K2 data (Angus et al., 2016b), as well as new gyrochronology calibrations using *Kepler* asteroseismic targets (Angus et al., 2015). She will lead the effort to measure and publish rotation periods for all K2 sources, and lead the graduate student in measuring ages for field stars.

Covey

Kipping

Agueros

5 Relevance to NASA Programs

history of MWY, age of planet systems, TESS

6 Plan of Work

Year 1: process all rotation period data
Year 2: write papers

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