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Calibrating gyrochronology using Galactic kinematics

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ABSTRACT

Gyrochronology, the method of inferring the age of a star from its rotation period, could provide ages for billions of stars over the coming decade of time-domain astronomy. However, the gyrochronology relations remain poorly calibrated due to a lack of precise ages for old, cool main-sequence stars. Now however, with proper motion measurements from Gaia, Galactic kinematics can be used as an age proxy, and the magnetic and rotational evolution of stars can be examined in detail. We demonstrate that kinematic ages, inferred from the velocity dispersions of groups of stars, beautifully illustrate the time and mass-dependence of the gyrochronology relations. We use the kinematic ages of field stars, plus benchmark clusters and asteroseismic stars, to calibrate a new empirical Gaussian process gyrochronology relation, that fully captures the complex rotational evolution of cool dwarfs over a range of masses and ages. We use cross validation to demonstrate that this relation accurately predicts ages for FGKM dwarfs.

Keywords: Stellar Rotation — Stellar Evolution — Stellar Activity — Stellar Magnetic Fields — Low Mass Stars — Solar Analogs — Milky Way Dynamics

1. INTRODUCTION

Low mass dwarfs are the most common stars in the Milky Way, and their ages could reveal the evolution of Galactic stellar populations and planetary systems. However, the ages of GKM stars are difficult to measure because their luminosities and temperatures evolve slowly on the main sequence. Fortunately, rotation-dating, or 'gyrochronology' provides a promising means to measure precise ages for these cool dwarfs. The rotation periods of these stars evolve relatively rapidly, and a fully calibrated gyrochronology model that captures the time and mass-dependence of stellar spin down could provide ages that are precise to within 20% for millions of Milky Way stars in the time-domain era (Epstein & Pinsonneault 2014; Najita et al. 2016; Angus et al. 2019).

With the thousands of new photometric rotation period measurements provided by specialized ground and space-based missions (particularly *Kepler*/*K2* and *TESS* Borucki et al. 2010; Howell et al. 2014; Ricker et al. 2015), we are making progress towards the ultimate goal for rotation-dating: a fully calibrated gyrochronology relation, applicable to GKM main-sequence stars of all ages. A lack of low-mass and old calibration stars has previously limited the mass and age coverage of gyrochronology relations, which can only be calibrated using stars with precise age and rotation period measurements. Historically, the calibration sample has been limited to open clusters and asteroseismic stars. Open clusters provide good mass coverage for young stars: rotation periods have been measured for F through mid M dwarfs for stars in clusters with precisely measured ages up to around 700 Myr. Asteroseismic stars provide reasonable age coverage for hot stars: seismic masses and photometric surface rotation periods have been measured for F, G and early K dwarfs for stars as old as 10 Gyr. However, neither asteroseismology nor cluster analysis can provide rotation periods and ages for old, late K and M dwarfs. In addition, cluster and asteroseismic stars generally provide sparse coverage of the rotation period-effective temperature plane, and cannot reveal the detailed evolution of stellar rotation rates. As a result, most empirical gyrochronology relations are only reliable for G dwarfs up to Solar age, K dwarfs up to 2-3 Gyr, and early M dwarfs up to < 1 Gyr. For this reason, the rotational evolution of cool dwarfs is not well understood. However, as we showed in **?**, *kinematic* ages can be used to turn field stars, observed by *Kepler*, into a calibration sample that provides good mass and age coverage. Although the *Kepler* sample does not include late M dwarfs, it can still be used to extend gyrochronology relations to much older ages for late K and early M dwarfs.

By adding the ages and rotation periods of thousands of field stars to the open cluster and asteroseismic calibration sample, we can calibrate a gyrochronology relation that is applicable to FGK and early M dwarfs between the ages of ∼500 Myr and 8 Gyr.

- How are rotation periods measured?

1.1. *Using kinematics as an age proxy*

In general, the velocity dispersions of stars in the Galactic thick disk are observed to increase with age (*e.g.* Casagrande et al. 2011; Aumer & Binney 2009)

In Angus *et al.* (2020) we demonstrated that Galactic kinematics can be used to explore the evolution of stellar rotation. We calculated the velocity dispersions of groups of stars with similar rotation periods and effective temperatures to show that K dwarfs spin down more slowly than G dwarfs. Their rotational evolution appears to 'stall' after around 1 Gyr, in a manner that reflects the behavior of K dwarfs observed in open clusters (Curtis et al. 2019). At young ages ($\sim 0.5 - 1$ Gyr), K dwarfs spin more slowly than G dwarfs of the same age, because their deeper convection zones generate stronger magnetic fields, which leads to more efficient magnetic braking. However, at old ages ($\gtrsim 1$ Gyr) K dwarfs rotate at the same rate, or more rapidly than G dwarfs of the same age. The leading theory for this phenomenon is that the angular momentum of the radiative cores and convective envelopes of K dwarfs evolve separately at young ages. The envelope loses angular momentum via magnetic braking while the core continues to spin rapidly. Over time however, angular momentum is transported across the interface between the two zones, and momentum from the rapidly spinning interior surfaces, inhibiting the deceleration of the outer envelope. With a mass-dependent timescale for core-envelope coupling, semi-empirical models are able to reproduce the rotation periods of field and cluster stars (Spada & Lanzafame 2019; Curtis et al. 2019, Angus *et al.*, 2020).

Most stars with rotation periods measured from *Kepler* data do not have RV measurements[1], so in Angus *et al.* (2020), we used $v_{\mathbf{b}}$, velocity in the direction of Galactic latitude, b, as a stand-in for $v_{\mathbf{z}}$. In the Galactic coordinate system, velocities can be calculated from 3D positions: RA (α), dec (δ) and parallax (π) and 2D proper motions, proper motion in RA (μ_α) and dec (μ_δ). So $v_{\mathbf{b}}$ can be calculated without RV measurements, but is still a close approximation to $v_{\mathbf{z}}$ for *Kepler* stars by virtue of its low Galactic latitude. Unfortunately however, given that AVRs are calibrated in *galactocentric* coordinates ($v_{\mathbf{x}}$, $v_{\mathbf{y}}$, $v_{\mathbf{z}}$), we could not directly translate $v_{\mathbf{b}}$ velocity dispersions to ages.

In this paper, our aim was to use kinematic ages to calibrate a new gyrochronology relation. Three main technological improvements to the analysis applied in Angus *et al.* (2020) were required to calibrate this new relation. Firstly, we calculated *vertical* velocity, $v_{\mathbf{z}}$, rather than velocity in the Galactic latitude direction, $v_{\mathbf{b}}$, for each star. We did this by inferring $v_{\mathbf{x}}$, $v_{\mathbf{y}}$, and $v_{\mathbf{z}}$, while marginalizing over missing RV measurements, using a hierarchical Bayesian model (see section 2.2). Secondly, instead of making a single estimate of the velocity dispersion of a group of stars, we calculated the velocity dispersion of groups of stars, centered on each star, *i.e.* we calculated a moving, or rolling dispersion (see section 2.3). These velocity dispersions were then converted into ages using an AVR (**?**) in section **??**. Thirdly, we used a Gaussian process model to capture the complexities of stellar rotational evolution and calibrated a new GP-based gyrochronology relation using our new kinematic ages, plus benchmark cluster and asteroseismic stars in section **??**.

[1] although RVs for most will be released in *Gaia* DR3

2. METHOD

2.1. *Data*

This study focuses on stellar rotation in the original *Kepler* field. This is partly because *Kepler* provides the largest sample of published, homogeneously measured rotation periods, and partly because its low Galactic latitude allows us to marginalize over missing RV measurements and approximate vertical velocity, $v_\mathbf{z}$. We combined three rotation period catalogs constructed from original *Kepler* data: McQuillan et al. (2014), **?** and García et al. (2014).

2.2. *Inferring 3D velocities (marginalizing over missing RV measurements)*

It has been demonstrated that the dispersion in vertical velocity, $v_\mathbf{z}$ for a group of stars increases with the age of that group (citations). However, velocities in Galactocentric coordinates, $v_\mathbf{x}$, $v_\mathbf{y}$ and $v_\mathbf{z}$, can only be calculated with full 6-D position and velocity information, *i.e.* proper motions, position and radial velocity. In **?** we introduced the idea that kinematic ages could be used to calibrate gyrochronology and showed, in the appendix of that paper, that velocity, $v_\mathbf{b}$ in the Galactic frame, which can be calculated without an RV measurement, can be used as an approximation to $v_\mathbf{z}$ for *Kepler* stars. This is because the *Kepler* field of view lies at relatively low Galactic latitudes, ($\sim 5 - 20°$), so the z-direction is similar to the b-direction for *Kepler* stars. However, $v_\mathbf{b}$ is only a close approximation to $v_\mathbf{z}$ at extremely *low* latitudes, and even in the *Kepler* field, kinematic ages calculated with $v_\mathbf{b}$ instead of $v_\mathbf{z}$ are systematically larger because of extra noise introduced by the imperfect translation between $v_\mathbf{b}$ and $v_\mathbf{z}\dot{}$In order to calculate accurate vertical velocities and therefore ages, the appropriate approach is to *infer* $v_\mathbf{z}$ by marginalizing over missing RV measurements.

Three-dimensional velocities in galactocentric coordinates: $v_\mathbf{x}$, $v_\mathbf{y}$, and $v_\mathbf{z}$ can only be directly computed via a transformation from 3D velocities in another coordinate system, like the equatorial coordinates provided by *Gaia*: μ_α, μ_δ, and RV. For stars with no measured RV in *Gaia* DR2, $v_\mathbf{x}$, vy, and $v_\mathbf{z}$ can still be inferred from positions and proper motions alone, by marginalizing over missing RV measurements. For each star in our sample, we inferred $v_\mathbf{x}$, $v_\mathbf{y}$, and $v_\mathbf{z}$ from the 3D positions and proper motions provided in the *Gaia* DR2 catalog (Brown et al. 2011). We also simultaneously inferred distance, instead of using $1/\pi$, to model velocities (**?**).

Using Bayes rule, the posterior probability of the parameters given the data can be written:

$$p(v_\mathbf{xyz}, D|\mu_\alpha, \mu_\delta, \alpha, \delta, \pi) = p(\mu_\alpha, \mu_\delta, \alpha, \delta, \pi|v_\mathbf{xyz}, D)p(v_\mathbf{xyz})p(D), \tag{1}$$

where D is distance, α is Right Ascension (RA), δ is declination (dec), π is parallax, μ_α is proper motion in RA, and μ_δ is proper motion in dec. The prior over log(distance) and velocities was a multivariate Gaussian with mean and covariance determined from the distance and velocity distributions of *Kepler* targets with RV measurements.

The posterior PDF was explored using `emcee` (**?**), an affine-invariant, ensemble MCMC sampler.

Initialization.

We found that 10,000 samples with 16 walkers was sufficient to calculate a converged autocorrelation time, and produce 150-500 independent samples per parameter.

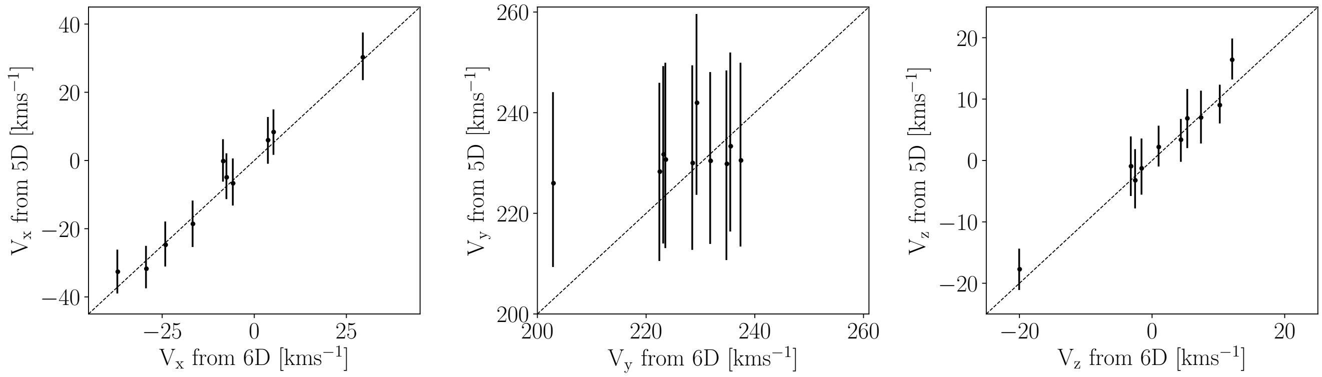
Over 3000 stars in the McQuillan et al. (2014) sample do have RV measurements and provide an opportunity to test this method of inferring velocities. Figure **??** shows the velocities of these 3000 stars, calculated using RV measurements, compared with their inferred velocities.

2.3. *Calculating velocity dispersions*

A kinematic age can be calculated from the velocity dispersion (*e.g.* the standard deviation or Median Absolute Deviation, MAD, of velocities) of a group of stars. These velocity dispersions can then be converted into an age using an AVR (*e.g.* **??**). The major assumption underlying kinematic ages is that all stars used to calculate a velocity dispersion are *the same age*. So, in order to calculate kinematic ages from velocity dispersions for *Kepler* stars, it is necessary to group them by age. Fortunately, we can use the implicit assumption that underpins gyrochronology itself to group stars by age: that stars with the same rotation period and color are the same age. We discuss the implications of this assumption, and how our results would change if this assumption is false, in the Discussion of this paper (section **??**).

To calculate a $v_\mathbf{z}$ velocity dispersion and therefore age for each *Kepler* star, we grouped stars with their neighbors in $\log(P_\mathrm{rot})$–T_eff space. We experimented with two methods of grouping stars: using K-nearest neighbors, and using a fixed range in $\log(P_\mathrm{rot})$ and T_eff. In the K-nearest neighbors method, each star was grouped with the K-nearest stars in $\log(P_\mathrm{rot})$-T_eff space. Groups created this way span a small range of $\log(P_\mathrm{rot})$ and T_eff where the number density of

Figure 1. Vertical velocities calculated with full 6D information vs vertical velocities inferred without RV, for all 3000 McQuillan et al. (2014) stars with *Gaia* RV measurements.



stars is large, and a large range where the number density is small. However, all groups have the same number of stars. In the fixed range method, each star was grouped with stars whose $\log(P_{\rm rot})$s and $T_{\rm eff}$s fell within a certain range of their own. This method created groups with large numbers of stars in densely populated regions of the $\log(P_{\rm rot})$–$T_{\rm eff}$ plane, and small numbers of stars in sparsely populated regions, *i.e.* each group contains a different number of stars. However, the bin size was constant. To choose the best method, and to optimize for the parameters of each (K and $\log(P_{\rm rot})$ and $T_{\rm eff}$-range), we conducted a set of tests.

2.4. *Converting velocity dispersion to age with an AVR*

2.5. *Comparing kinematic ages with asteroseismic and cluster ages*

2.6. *A Gaussian process gyrochronology relation*

3. RESULTS

4. DISCUSSION

5. CONCLUSION

This work was partly developed at the 2019 KITP conference 'Better stars, better planets'. Parts of this project are based on ideas explored at the Gaia sprints at the Flatiron Institute in New York City, 2016 and MPIA, Heidelberg, 2017. This work made use of the gaia-kepler.fun crossmatch database created by Megan Bedell.

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