Exploring the ages of rotating stars using galactic dynamics: a novel approach to calibrating gyrochronology

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ABSTRACT

The rotational evolution of cool dwarfs is mostly unconstrained after around 2-3 billion years, and the gyrochronology relations are poorly calibrated beyond this time due to a lack of precise ages and rotation periods for old main-sequence stars. We use the velocities of populations of K dwarfs to reveal the rotational evolution of these cool stars at old ages. We find that groups of stars, selected to be the same age using a gyrochronology relation calibrated to the Praesepe cluster, do *not* have the same velocity dispersion at all temperatures; cooler stars have greater velocity dispersions than hotter stars. We interpret this to mean that these cooler stars are older than the hotter ones, which implies that the period-color relation of Praesepe is not appropriate for old stars. Futhermore, our results indicate that the slope of the period-color relation actually *inverts*: at young ages early K stars rotate more rapidly than late K stars, but beyond $\sim$ 2 Gyr they rotate more slowly. These observations could be reproduced by mass-dependent dynamical heating, where lower-mass stars experience a greater rate of dynamical heating than higher-mass stars, however we find no evidence for mass-dependent heating within K and M dwarfs in the *Kepler* field.

1. Introduction

1.1. Gyrochronology

It is well established that the rotation periods of FGKM dwarfs increase over time (Skumanich 1972). This characteristic of main-sequence (MS) stars allows them to be dated using their rotation periods, via gyrochronology (*e.g.* **??**Barnes 2003, 2007; **?**; Meibom et al. 2011; **?**), which is particularly useful since the ages of MS stars are difficult to measure via isochrone placement. It is also well established that stars of the same age but different masses have different rotation periods (*e.g.* **??**), thought to be caused by the deeper convective zones, and therefore stronger magnetic dynamos (and more efficient magnetic braking) in lower-mass stars. However, an underlying assumption behind many empirical gyrochronology relations is that the relationships between rotation period and photometric color[1], and rotation period and age are *separable*, meaning that the period-color relation is the same at all ages and the period-age relation is the same at all colors (*e.g.* Barnes 2003, 2007; Mamajek and Hillenbrand 2008; Meibom et al. 2011; Angus et al. 2015; Angus et al. 2019). Not all gyrochronology models follow this form, particularly those motivated based on stellar structure and evolution theory or with a Rossby number, rather than rotation period dependence (*e.g.* **???**). It was recently shown that old field stars rotate more rapidly than a simple, separable gyrochronology relation would predict (Angus et al. 2015; van Saders et al. 2016, 2018; Metcalfe and Egeland 2019), and that a mass-dependent modification to the classical $P_{\rm rot} \propto t^{\frac{1}{2}}$ spin-down law (Skumanich 1972) is required to reproduce the data (van Saders et al. 2016, 2018). An even more recent analysis of the 1.1 Gyr open cluster, NGC 6811, provides further indication that the exponent of the period-age relation is mass and time-dependent (Curtis et al. 2019). This cluster has a flattened relationship between rotation period and color and the G dwarfs rotate at the same rate as the K dwarfs.

In this paper, we tested the Angus et al. (2019) gyrochronology relation, a separable relation, calibrated using the period-color relation of Praesepe (in *Gaia* $G_{BP} - G_{RP}$ color) and the period-age relation of Praesepe and the Sun. The large number of Praesepe members with precise rotation periods from the *K2* mission (Douglas et al. 2017; Rebull et al. 2017), spanning spectral types F through early M, makes it the ideal cluster for calibrating the period-color relation of stars at 650 Myrs. This relation accurately describes the rotation periods of F and G stars up to around 2.5 Gyr (the age of NGC 6819 – the oldest cluster with available rotation periods), but over-predicts the rotation periods of K dwarfs in the 1.1 Gyr NGC 6811 cluster. Very few reliable age estimates exist for K dwarfs with rotation periods older than 1.1 Gyr, or between the ages of $\sim$ 800 Myr–1.1 Gyr so the rotational evolution of middle-aged K dwarfs is a mystery[2]. For this reason, we used a population-based stellar age indicator, velocity dispersion, to investigate the period-color relations at old ages in the field.

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[1]As the directly observable quantity, color is often used as a mass proxy, and empirical gyrochronology relations are usually calibrated in color, rather than mass or effective temperature.

[2]The oldest M dwarfs with reliable ages and rotation periods are members of Praesepe ($\sim$ 650 Myrs), so even less is known about their rotational evolution.

1.2. Kinematics as an age proxy

Stars are thought to be born in the thin disk of the Milky Way (MW), orbiting the center of the galaxy with a low out-of-plane, or vertical, velocity (W, or v_z), just like the star-forming molecular gas observed in the disk today (*e.g.* **??**Aumer and Binney 2009; **?**; Aumer et al. 2016). Young stars have relatively small vertical velocities, but gain momentum in the vertical direction over time (*e.g.* Nordström et al. 2004; Holmberg et al. 2007, 2009; Aumer and Binney 2009; **?**). Although the cause of orbital heating is not well understood, interactions with giant molecular clouds, spiral arms and the galactic bar are thought to play an important role (see Sellwood 2014, for a review of secular evolution in the MW). Although the velocity of any individual star will only provide a weak age constraint, the velocity dispersion of a group of stars can indicate whether, on average, that group is old or young relative to other groups. In this work we compare the velocity dispersions of groups of stars to ascertain which groups are older and which younger and draw conclusions based on the implied relative ages of populations. The age-velocity dispersion relations (AVRs) are still actively being calibrated, so it is difficult to directly compare gyrochronal ages with kinematic ones. However, regardless of the exact relation between velocity dispersion and stellar age, it is expected to be a monotonic relationship, therefore velocity dispersion can be used effectively to *rank* groups of stars by age.

Vertical action is a better age indicator than vertical velocity (**?**), although still only a weak age indicator for individual stars (Beane et al. 2018), however both vertical action (J_z) and vertical velocity ($v_{\mathbf{z}}$/W) can only be calculated with full 6-dimensional position and velocity information. Unfortunately, most stars with measured rotation periods do not have radial velocity (RV) measurements because they are relatively faint *Kepler* targets ($\sim$11th-18th magnitudes). For this reason, we used velocity in the direction of galactic latitude, $v_{\mathbf{b}}$. The *Kepler* field is positioned at low galactic latitude (b=5-20°), so $v_{\mathbf{b}}$ is a close (although imperfect – see section 2) approximation to $v_{\mathbf{z}}$.

1.3. The data

We used the publicly available *Kepler*-*Gaia* DR2 crossmatched catalog[3] to combine the McQuillan et al. (2014) catalog of stellar rotation periods, measured from *Kepler* light curves, with the *Gaia* DR2 catalog of parallaxes, proper motions and apparent magnitudes. Reddening and extinction from dust was calculated for each star using the Bayestar dust map implemented in the `dustmaps` *Python* package (M. Green 2018), and `astropy` (Astropy Collaboration et al. 2013). We estimated effective temperatures from dereddened *Gaia* $G_{BP} - G_{RP}$ color, using an 8th-order polynomial relation calibrated using .... stars ask Jason for details.

$$\mathrm{T_{eff}} = 8960 - 4802C + 1931C^2 - 2446C^3 + 2669C^4 - 1324C^5 + 301C^6 - 26C^7, \qquad (1)$$

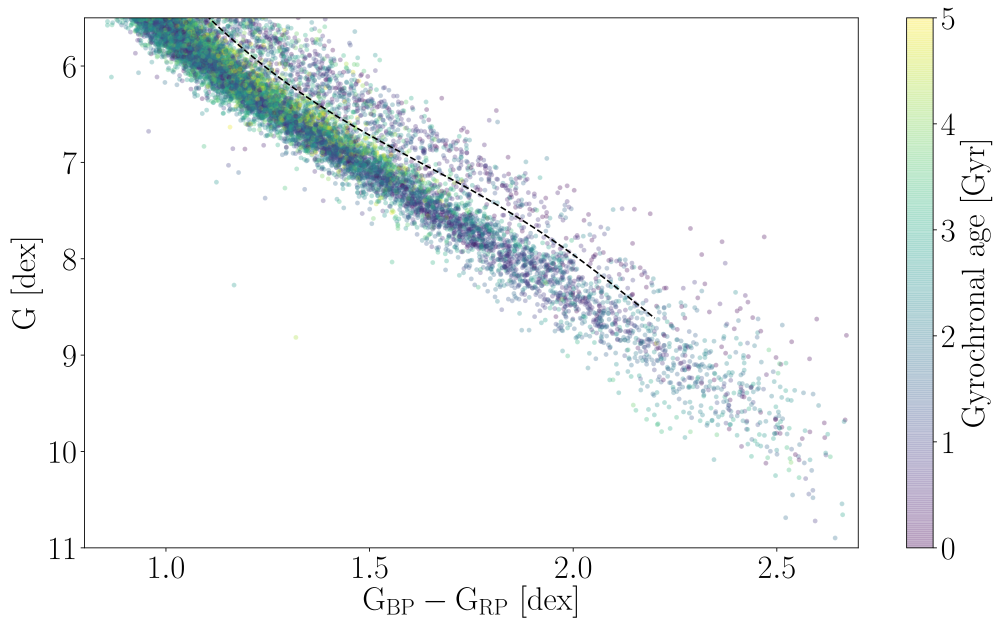
where C is *Gaia* $G_{BP} - G_{RP}$.

Visual binaries and subgiants were removed from the sample by applying cuts to the color-magnitude diagram (CMD), shown in figure 1. A 6th-order polynomial was fit to the main sequence and raised by 0.27 dex to approximate the division between single stars and visual binaries. All stars above this line were removed from the sample. Subgiants were also removed by eliminating stars brighter than 6th magnitude in *Gaia* G-band.

The `Pyia` (Price-Whelan 2018) and `astropy` (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018) *Python* packages were used to calculate stellar velocities. `Pyia` calculates velocity samples from the full *Gaia* uncertainty covariance matrix via Monte Carlo sampling. It therefore not only incorporates uncertainties on the *Gaia* positions parallaxes and proper motions, it also accounts for the *covariance* between these properties. Stars with negative parallaxes, parallax signal-to-noise ratios less than 10, stars fainter than 16th magnitude, stars with absolute $v_\mathbf{b}$ uncertainties greater than 1 kms^{-1} and stars with galactic latitudes greater than 15° were removed from the sample. Because $v_\mathbf{b}$ is only a close approximation to $v_\mathbf{z}$ at low galactic latitudes, and because latitude is correlated with stellar mass (lower mass stars are older and tend to be preferentially located at high b, although this trends is greatly reduced for stars cooler than 5000 K), we found that excluding stars with $b > 15°$ reduced the number of $v_\mathbf{b}$ outliers at low stellar mass. 15° was found to be an adequate compromise between maintaining a close relationship between $v_\mathbf{b}$ and $v_\mathbf{z}$ and retaining a sample large enough to provide meaningful results. Reducing this cut to 10° resulted in a sample size too small to reveal trends in the data.

[3]Available at gaia-kepler.fun

Fig. 1.— Dereddened MS *Kepler* stars with McQuillan et al. (2014) rotation periods on the *Gaia* CMD. We excluded visual binaries by removing stars above the dashed line. Points are colored by their gyrochronal age, according to the Angus et al. (2019) gyrochronology relation. A general age gradient is visible across the main sequence.



2. Results

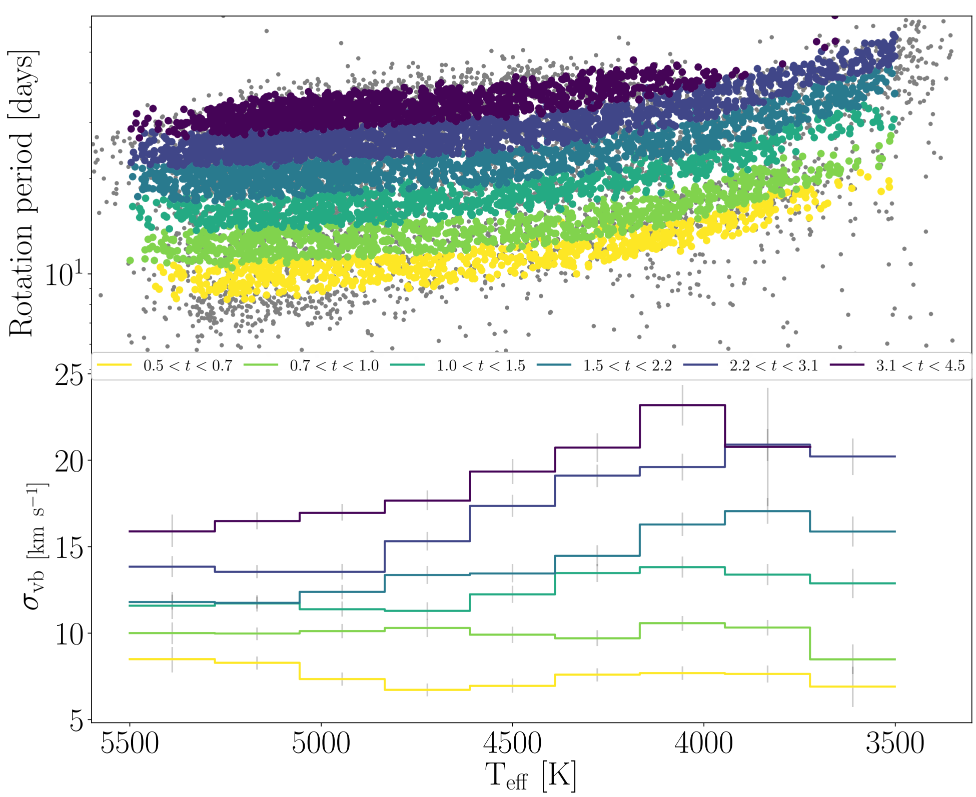
2.1. Velocity dispersion of coeval groups

To explore the relationship between rotation period, T_{eff} and age, we selected groups of stars within different age ranges (where age was calculated using the Angus et al. 2019, gyrochronology relation), and calculated the velocity dispersion: the standard deviation of velocities in the direction of increasing galactic latitude, $\sigma_{v\mathbf{b}}$, as a function of effective temperature for each age group. We performed 3σ sigma-clipping on the stellar velocities in each age and temperature bin to remove non-Gaussian outliers. Without sigma-clipping, we found that a small number of high velocity outliers at the low-temperature end of our sample substantially raised the velocity dispersion for cooler stars. Ages were calculated using dereddened *Gaia* $G_{BP} - G_{RP}$ color, however throughout this paper we show rotation periods as a function of effective temperature, T_{eff}. We chose to use $T_{\mathrm{eff}}$and not photometric color in this analysis as it is the linear quantity and therefore easier to divide into bins of roughly equal numbers of stars.

The top panel of figure 2 shows the full McQuillan et al. (2014) sample (excluding visual binaries and subgiants) in grey, with coeval groups shown in color. The color of the points corresponds to the age ranges specified in the legend (in Gyr), which also apply to the lines in the lower panel. The bottom panel shows the velocity dispersion, $\sigma_{v\mathbf{b}}$ of each age group, as a function of effective temperature. Late M dwarfs were not included in our analysis because such faint stars cannot be observed at large heights above the plane (because of the low galactic latitude of the *Kepler* field, stars at high-Z are more distant), which introduces a mass-dependent velocity bias: cooler populations of stars are skewed towards lower velocity dispersions. The coolest temperature bins in the lower panel of figure 2 have low velocity dispersions, indicating that this effect may already become important at temperatures lower than $\sim$ 4000 K.

Overall, figure 2 shows that velocity dispersion increases with gyrochronal age across all temperatures, implying that both velocity dispersion and rotation periods increase with age as expected. The constant velocity dispersion of young stars as a function of temperature shows that the Praesepe-calibrated gyrochronology relation accurately predicts the relative ages of *young* field stars. In contrast however, velocity dispersion increases as a function of temperature for old stars, meaning the Angus et al. (2019) gyrochronology relation underpredicts the ages of old, late-K dwarfs (or overpredicts the ages of old early-K dwarfs). This indicates that the relationship between period and photometric color or T_{eff} flattens out over time. In other words, the lines of constant age sweeping diagonally upwards in the top panel of figure 2 are too steeply sloped at old ages.

Fig. 2.— Top: rotation period vs effective temperature for stars in the McQuillan et al. (2014) catalog. The full catalog, with subgiants and visual binaries removed is shown in grey, and stars selected to be in different age groups (between 3500 and 5500 K) are overlayed in color. These age groups were selected using the Angus et al. (2019) gyrochronology relation. The legend in the center of the figure lists the age range, in Gyr, of each group. Bottom: velocity dispersion vs effective temperature for each age group. The color of the line corresponds to the color of the group shown in the top panel. If the gyrochronal model were correct at all ages, and the stars in each group were the same age across temperatures, the velocity dispersion would be constant as a function of $T_{\rm eff}$. However, the velocity dispersions of the oldest age groups increase with $T_{\rm eff}$, indicating the Angus et al. (2019) gyrochronology model underpredicts the the ages of late-K dwarfs relative to the ages of early K dwarfs at old ages.

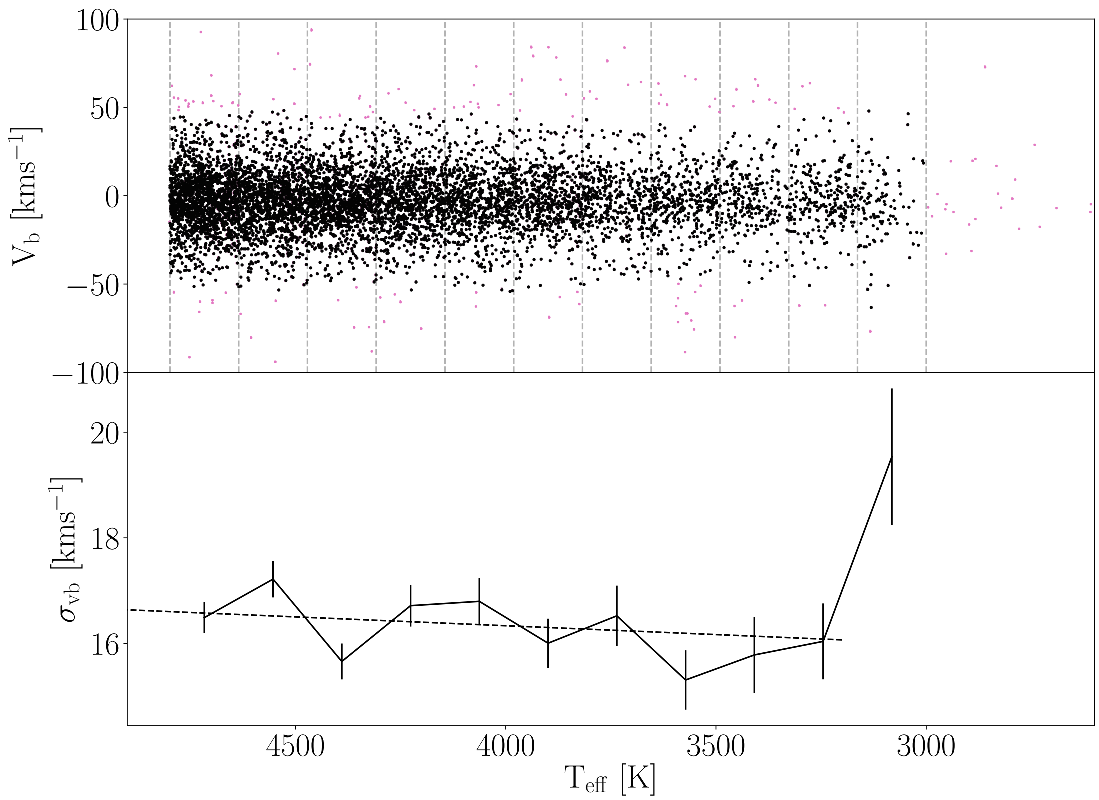


2.2. Mass-dependent heating

An alternative explanation for this phenomenon is that lower-mass stars experience greater velocity changes when gravitationally perturbed and are more efficiently dynamically heated. Mass-dependent orbital heating has not been unambiguously observed in the galactic disk because of the strong anti-correlation between stellar mass and stellar age. Less massive stars do indeed have larger velocity dispersions, however they are also older on average. This mass-age degeneracy is highly reduced in M dwarfs because their main-sequence lifetimes are longer than the age of the Universe, however no evidence for mass-dependent heating has been detected in these low mass stars (Faherty et al. 2009). To investigate further, we selected late K and M dwarfs observed by both *Kepler* and *Gaia*, whose MS lifetimes exceed around 11 Gyrs and are therefore representative of the initial mass function. We selected all *Kepler* targets with dereddened *Gaia* $G_{BP} - G_{RP}$ colors greater than 1.2 (corresponding to an effective temperature $\lesssim$ 4800 K) and absolute *Gaia* G-band magnitudes < 4. We also eliminated visual binaries by removing stars above a 6th order polynomial, fit to the MS on the *Gaia* CMD. We then applied the same quality cuts as described in section 1.3. To search for evidence of mass-dependent heating we calculated the ($v_\mathbf{b}$) velocity dispersion of stars in effective temperature bins. Again, we applied sigma clipping to remove high velocity outliers before calculating the standard deviation of stars in each bin. Figure 3 shows velocity and velocity dispersion as a function of effective temperature (calculated by transforming dereddened *Gaia* colors using equation 1). Velocity dispersion very slightly *decreases* with decreasing temperature, (the opposite of the trend expected for mass-dependent heating) however the slope is only inconsistent with zero at the 1.3 σ level. This trend may be due to a selection bias: cooler stars are fainter and therefore typically closer, with smaller heights above the galactic plane and smaller velocities. The essential point here is that the increasing velocity dispersion with age and decreasing temperature that is evident in figure 2 is not a result of an intrinsically larger velocity dispersion for low-mass stars, nor is it a result of the selection function. Since we use $v_\mathbf{b}$, not $v_\mathbf{z}$ in this analysis, it is possible that the anti-correlation between T_{eff} and galactic latitude, b, could influence these results: stars at higher latitudes would have additional velocity components in the $\mathbf{x}$ and $\mathbf{y}$ directions, which could increase $v_\mathbf{b}$ but not $v_\mathbf{z}$. However, since the relationship between $\sigma_{v\mathbf{b}}$ and T_{eff} is positively, not negatively correlated for cool stars in the *Kepler* field, this effect is probably too small to influence our results. We performed the same analysis on the 537 stars in this sample with RVs in *vertical* velocity ($v_\mathbf{z}$) and found the slope of the velocity dispersion-temperature relation was consistent with zero.

Figure 3 indicates that mass-dependent heating does not strongly affect the McQuillan et al. (2014) sample of rotating *Kepler* stars. For this reason, we assume that age difference is the only significant cause of velocity dispersion differences between groups. In other words,

Fig. 3.— Top: Stellar velocity ($v_{\mathbf{b}}$) as a function of T_{eff} for *Kepler* K and M dwarfs. Vertical lines indicate different T_{eff}-groupings used to calculate velocity dispersion. Pink stars were not included in velocity dispersion calculations as they were either removed as outliers during a sigma clipping process, or they lie at the sparcely populated, extremely cool end of the temperature range. Velocity dispersion and T_{eff} are slightly correlated, indicating that mass-dependent heating does not significantly affect low-mass stars in the *Kepler* field.



($v_{\mathbf{b}}$) velocity dispersion is a reliable age proxy for the McQuillan et al. (2014) sample.

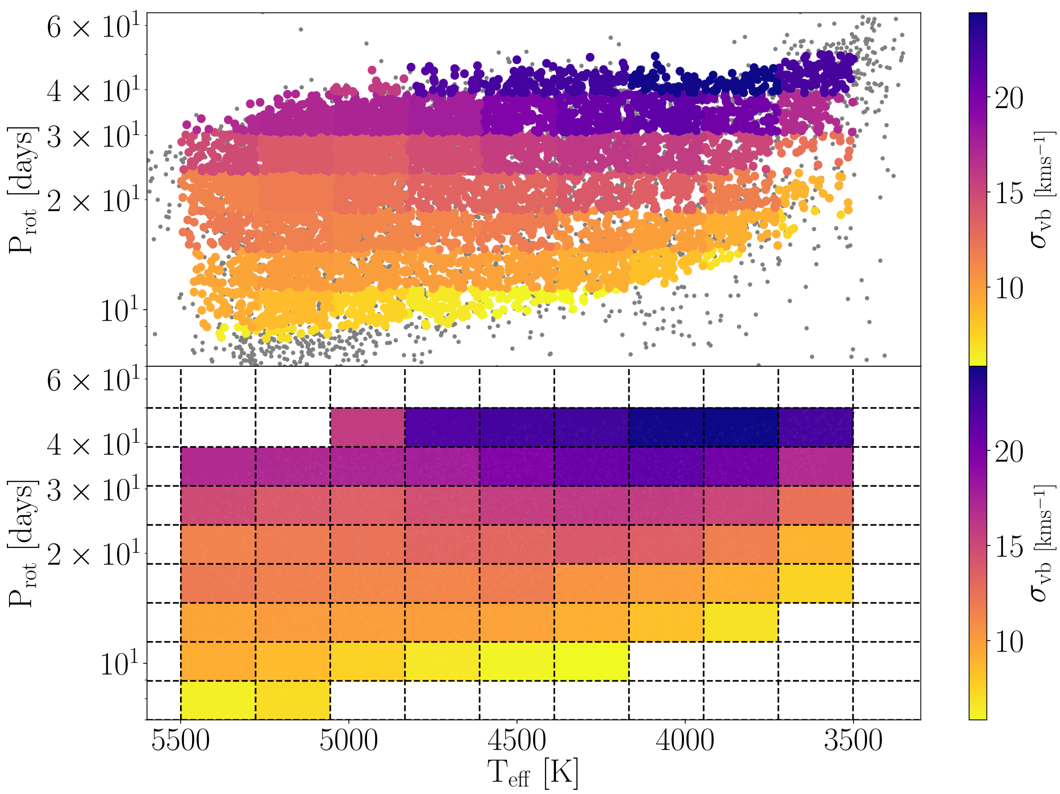
2.3. The period gap

An unsolved mystery within gyrochronology is the origin of the rotation period gap, first identified by McQuillan et al. (2013). This gap can be seen in figure 2 as an underdensity of points between the 0.7-1.0 and 1.0-1.5 Gyr age ranges and roughly follows a line of constant gyrochronal age of around 1.1 Gyr (according to the gyrochronology relation of Angus et al. 2019). Several explanations for its origin have been proposed, including a discontinuous star formation history (McQuillan et al. 2013; Davenport 2017; Davenport and Covey 2018), a rapid change in magnetic field structure (Reinhold et al. 2019), and erroneous rotation period measurements that are incorrect by a factor of two (Koen 2018). The latter explanation can be ruled out because stars below the gap have smaller velocity dispersions than the stars above the gap, indicating that they are kinematically younger (McQuillan et al. 2013; Davenport and Covey 2018), as evident in figure 2. For stars below the gap, in the 0.7-1.0 Gyr age range shown in figure 2, velocity dispersion is relatively constant as a function of temperature, however above the gap, in the 1.0-1.5 Gyr age range and older, velocity dispersion increases with T_{eff}. The coolest stars in the 1.0-1.5 Gyr age range have the same velocity dispersion as the hottest stars in the age range above which indicates that the period-T_{eff} relations are *flat* at these rotation periods. It may be a coincidence that the gyrochronology relations seem to only flatten off *above* the period gap, or it may be that the period gap is located at magnetic transition period. We lack a sufficient quantity of data to investigate in detail but new field star rotation periods from the *K2* and *TESS* missions may be able to validate or rule out this hypothesis in the future.

2.4. The period-T_{eff} relations, revealed

Figure 4 shows rotation period vs. T_{eff} for our sample, coloured by ($v_{\mathbf{b}}$) velocity dispersion. Here, velocity dispersion was calculated for groups of stars in uniformly-spaced bins in $\log_{10}$(period) and temperature. If we assume that mass dependent heating doesn't affect this sample, and $v_{\mathbf{b}}$ at low galactic latitudes is an unbiased tracer of $v_{\mathbf{z}}$, $v_{\mathbf{b}}$ velocity dispersion can be interpreted as an age proxy and stars plotted in a similar color in figure 4 are similar ages. Interpreted this way, it appears that rotation period *decreases* with decreasing effective temperature at old ages. This is a paradigm shift for gyrochronology because stellar spin-down rate is thought to be directly tied to magnetic field strength, and the deeper convection zones of cooler stars generate stronger magnetic fields which *should* lead to more

Fig. 4.— Rotation period vs effective temperature for stars in the McQuillan et al. (2014) sample, colored by the velocity dispersions of stars in restricted period and temperature ranges.



efficient angular momentum loss. A similar phenomenon has been observed in the 1.1 Gyr NGC 6811 cluster, where the rotation periods of mid-K dwarfs are faster than expected; their rotational evolution appears to have stalled, and the period-$T_{\rm eff}$ relation is flat (Curtis et al. 2019). NGC 6811 straddles the rotation period gap and may be the 'missing link' that connects two epoch of stellar spin-down: an early stage where the period-$T_{\rm eff}$ relation for K dwarfs has a negative slope and a late stage where it has a positive slope. In this case the period gap may delineate the transition between these two regimes and is the point at which stellar magnetic dynamos likely undergo a dramatic structural shift.

Figure 4 also shows that the (kinematically) oldest stars with measured rotation periods are cooler than 4500 K. This may be because cooler stars remain active for longer, and their rotation periods can therefore be measured at older ages.

3. Conclusion

We examined the gyrochronology relations using the velocity dispersions of field stars with measured rotation periods. We found that old groups of K dwarfs selected to be coeval using the Angus et al. (2019) gyrochronology relation do *not* have the same velocity dispersion across all temperatures. It appears that the period-$T_{\rm eff}$ relation changes shape over time: rotation period is negatively correlated with $T_{\rm eff}$ at young ages, and positively correlated at old ages. The relation appears to start flattening out after ∼1 Gyr (see figure 2), potentially around the same age, or just older than the period gap which is located at a (gyro) age of around ∼1.1 Gyr. This gap may represent a significant transitional epoch in the magnetic behavior of stars. Finally, when velocity dispersion is interpreted as an age proxy, it appears that the oldest stars in the McQuillan et al. (2014) catalog are cooler than 4500 K, which suggests that lower-mass stars remain active for longer and their rotation periods can be measured at older ages.

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This work made use of the gaia-kepler.fun crossmatch database created by Megan Bedell

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