A Temporary Epoch of Stalled Spin-down for Low-mass Stars: Insights from NGC 6811 with Gaia and Kepler

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Abstract

Stellar rotation was proposed as a potential age diagnostic that is precise, simple, and applicable to a broad range of low-mass stars (≤1 M⊙). Unfortunately, rotation period (Prot) measurements of low-mass members of open clusters have undermined the idea that stars spin down with a common age dependence (i.e., Prot ∝ (age)1/2): K dwarfs appear to spin down more slowly than F and G dwarfs. Agüeros et al. interpreted data for the ≈1.4 Gyr-old cluster NGC 752 differently, proposing that after having converged onto a slow-rotating sequence in their first 600–700 Myr (by the age of Praesepe), K dwarf Prot stall on that sequence for an extended period of time. We use data from Gaia DR2 to identify likely single-star members of the ≈1 Gyr-old cluster NGC 6811 with Kepler light curves. We measure Prot for 171 members, more than doubling the sample relative to the existing catalog and extending the mass limit from ≈0.8 to ≈0.6 M⊙. We then apply a gyrochronology formula calibrated with Praesepe and the Sun to 27 single G dwarfs in NGC 6811 to derive a precise gyrochronological age for the cluster of 1.04 ± 0.07 Gyr. However, when our new low-mass rotators are included, NGC 6811’s color–Prot sequence deviates away from the naive 1 Gyr projection down to Teff ≈ 4295 K (K5V, 0.7 M⊙), where it clearly overlaps with Praesepe’s. Combining these data with Prot for other clusters, we conclude that the assumption that mass and age are separable dependencies is invalid. Furthermore, the cluster data show definitively that stars experience a temporary epoch of reduced braking efficiency where Prot stall, and that the duration of this epoch lasts longer for lower-mass stars.

Key words: open clusters and associations: individual (NGC 6811, Pleiades, Praesepe) – stars: evolution – stars: rotation – stars: solar-type

Supporting material: figure set, machine-readable table

1. Introduction

Sun-like stars change very little over their main-sequence lifetimes, making their ages one of their most challenging properties to determine. However, knowing stellar ages, especially for low-mass stars (≤1 M⊙), is essential in this era of precision astrophysics. On the Galactic scale, our current inability to provide confident ages for these stars limits our understanding of the Milky Way’s star formation history and chemical enrichment. On the planetary-system scale, it negatively impacts the development of theories for planet formation and evolution.

Forty-seven years ago, Skumanich (1972) compared rotation for solar-mass members of young nearby clusters (the Pleiades, Ursa Major, and the Hyades) to the Sun, and noted that stars appeared to spin down according to the square-root of age, which has since become known as the Skumanich Law. Barnes (2003) built on this work to propose the use of rotation periods (Prot) as a clock, which he termed gyrochronology. A reliable rotation–age relation would be a boon to the study of these stars, because other techniques for obtaining their ages generally do not work (Soderblom 2010). For example, for K and M stars, relying on evolution off of the zero-age main sequence and the subsequent increase in luminosity or decrease in surface gravity cannot lead to meaningful constraints on ages, as these parameters are practically unchanged over the age of the universe.

Unfortunately, observational efforts to constrain the rotation–age relation, based largely on observations of open clusters, have made our hopes for a simple relation fade. For example, when comparing the color–Prot distributions for M35 (150 Myr) and M34 (220 Myr) to that for the Hyades (727 Myr), Meibom et al. (2007, 2009, 2011b) found that while the F and G dwarfs had spun down following the Skumanich Law, K-type Hyads appeared to rotate too rapidly relative to their younger counterparts in M35 and M34, after projecting each sample to a common age using Prot ∝ t−1/2. Meibom et al. (2011a) noted a similar behavior for the early K dwarfs in NGC 6811 (1 Gyr). Cargile et al. (2014) reached a similar conclusion upon comparing rotation data for Blanco 1 (132 Myr; Cargile et al. 2010) to these same clusters. These authors suggested that Sun-like FGK dwarfs spin down continuously, but with time dependencies that differ according to mass. Barnes (2007, 2003) derived gyrochronology relations that decoupled the mass and age dependence of stellar spindown. Any mass dependence could then be determined from the Prot sequences observed in young, nearby clusters, and the age index n, also known as the braking index, for the t−1 power law could be fitted for by comparing those sequences to the Sun’s Prot and age.

However, while retaining the coefficients for the Barnes (2007) gyrochronology equation, Angus et al. (2015) were forced to discard data for Praesepe (670 Myr) and NGC 6811. In Douglas et al. (2019), we calculated a differential gyrochronology age of 727 Myr for the Hyades relative to Praesepe, which we fixed to 670 Myr based on the median of several literature isochrone ages.
In addition, Agüeros et al. (2018) analyzed light curves from the Palomar Transient Factory (Law et al. 2009; Rau et al. 2009) for the ≈1.4 Gyr-old3 cluster NGC 752 and found that the cluster’s early K dwarfs had barely slowed relative to Praesepe’s, while the late K and early M dwarfs had not spun down at all, despite being about twice as old.

Here, we reexamine rotation in the 1 Gyr cluster NGC 6811. We use high-precision astrometry and photometry from Gaia to identify cluster members with Kepler light curves, which extends the 1 Gyr rotator sample from ∼0.8 M⊙ (Meibom et al. 2011a) down to ∼0.6 M⊙ (Section 2). Next, we compare our expanded sample to the rotation data for the younger cluster Praesepe, and show that while the F and G dwarfs have spun down as expected, the K dwarfs have not slowed at all in the intervening ∼350 Myr. Finally, we demonstrate that this cannot be due to K dwarfs simply spinning down more slowly than F/G dwarfs, but instead must be caused by a temporary period of stalled braking (Section 3). We conclude in Section 4.

2. New Rotators in NGC 6811

Below, we review the properties of NGC 6811, first observed by John Herschel in 1829 (Herschel 1833). We then expand the cluster’s membership with data from the second Gaia data release (DR2; Gaia Collaboration et al. 2018a) and determine the properties of these stars. We also discuss the rotation results from Meibom et al. (2011a) before measuring Prot for those stars with Kepler (Basri et al. 2005) light curves and producing a new color–Prot distribution for the cluster.

2.1. The Age, Metallicity, and Reddening of NGC 6811

Sandquist et al. (2016) presented a thorough analysis of NGC 6811, including the characterization of a detached partially eclipsing binary (EB), measurements of astroseismic parameters for helium-burning giants, study of the pulsating stars at the main-sequence turnoff, and an analysis of its color–magnitude diagram (CMD). While there is some tension between the age solutions for the two EB components, most of the data support an age for the cluster of 1 ± 0.05 Gyr (Sandquist et al. 2016), in agreement with the Janes et al. (2013) UBVRI photometric analysis.

Sandquist et al. (2016) also summarized the spectroscopic metallicity measurements in the literature from various sources, which agree on an approximately solar metallicity with values ranging from −0.02 to +0.04 dex. Finally, Sandquist et al. (2016) found an interstellar reddening value of $E(B - V) = 0.07 ± 0.02$ (corresponding to $A_V = 0.22$), while various literature values range from $E(B - V) = 0.05$ to $0.14$ ($A_V = 0.16$ to 0.43). This is consistent with the 3D dust map value built with Pan-STARRS 1 and 2MASS photometry, which estimates $A_V = 0.25 ± 0.06$ at 1.15 kpc (Green et al. 2018). In Section 3.1, we refine the reddening/extinction value by fitting a gyrochronology model to the color–period distribution and find $A_V = 0.15$.

2.2. Identifying NGC 6811 Members with Gaia

The Meibom et al. (2011a) study of rotation in NGC 6811 relied on a sample vetted with radial velocities (RVs) to clean the Kepler $(g - r)_KIC$ versus $g_{KIC}$ CMD. Gaia recently delivered high-precision astrometry (positions, proper motions, and parallaxes) and photometry $(G, G_{BP}, G_{RP})$ for $> 1.3 \times 10^9$ stars (Gaia Collaboration et al. 2018a). These data greatly simplify the process of identifying single-star members of open clusters (e.g., Gaia Collaboration et al. 2018b).

We determine the cluster’s DR2 proper motion ($\mu$) and parallax ($\pi$) from the 71 members identified by Meibom et al. (2011a): $\mu_0 \cos \delta = -3.39 \text{ mas yr}^{-1}$, $\mu_\delta = -8.78 \text{ mas yr}^{-1}$, and $\pi = 0.87 \text{ mas}$. There are 86,853 stars within 1° of NGC 6811’s center (a 19 pc search radius at $d = 1096 \text{ pc}$) in DR2 with $G < 20$ mag and usable astrometry and photometry, but only 485 satisfy our simple astrometric criteria: $\mu$ within 0.5 mas yr$^{-1}$ and $\pi$ within 0.3 mas of the median for these 71 stars (see top row of Figure 1).

After applying our astrometric cuts, we overplot the candidate cluster members on the Gaia CMD for the region around NGC 6811 (see the bottom row of Figure 1). The cluster’s CMD is visually well-fit with a PARSEC isochrone model (Bressan et al. 2012; Chen et al. 2014) for an age of 1 Gyr, solar composition, $A_V = 0.15$, and $(m - M) = 10.2$, as shown in the bottom middle panel of Figure 1.

We then use the Hyades main sequence from Gaia Collaboration et al. (2018b) to define an empirical single-star sequence, which we fit with a cubic basis spline to predict $M_G$ from $(G_{BP} - G_{RP})$. Next, we apply the Hyades model to the NGC 6811 astrometric candidates using the NGC 6811 extinction and distance modulus, and filter out stars that are offset by more than 0.5 mag in $M_G$ from the model.

We fit a cubic basis spline to the stars remaining in the NGC 6811 sample to define the cluster’s single-star sequence more accurately, and then reextract the single stars with a stricter cut of 0.25 mag. In this manner, we identify 322 likely single members along the main-sequence of NGC 6811 (see the bottom right panel of Figure 1). While this is not a complete census of the cluster’s membership, this new catalog is all that is required for this work, which focuses on the rotational behavior of single stars.8

2.3. Determining Stellar Properties

While the DR2 stellar properties pipeline (Apsis; Baile-Jones et al. 2013; Andrae et al. 2018) produced effective temperatures ($T_{\text{eff}}$) from the DR2 photometry for 1.61 × 108 stars with $G < 17$ mag and $3000 < T_{\text{eff}} < 10,000$ K, these notably do not incorporate the effects of reddening. We therefore generate a color–$T_{\text{eff}}$ relation using three separate catalogs of precisely characterized nearby stars: the Brewer et al. (2016) sample of FGK stars observed by the California Planet Search with Keck/High Resolution Echelle Spectrometer (HIRES), the Boyajian et al. (2012) sample of K and M dwarfs with interferometric radii and bolometric fluxes, and the Mann et al. (2015) M dwarfs characterized with optical

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5 Agúeros et al. (2018) inferred an age of 1.34 Gyr for NGC 752; Anthony-Twarog et al. (2014) found 1.45 Gyr. We average the two results and round it to 1.4 Gyr.
6 http://argonaut.skymaps.info

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7 $(\alpha, \delta) = 19^h37^m12^s, +46^\circ23^\prime15^\prime\prime$.
8 While characterizing the binary population is critical in any cluster, in this context binaries are contaminants. Binary companions may exert tidal or other physical effects on the primary star (e.g., Meibom & Mathieu 2005; Meibom et al. 2007; Douglas et al. 2016, 2017), causing us to locate stars incorrectly in the color–Prot plane, and leading us to misidentify trends or transitions in the period distribution.
and near-infrared spectroscopy. Deriving our own empirical relation also allows us to correct for NGC 6811’s metallicity.9

The temperatures of stars hotter than 4100 K in our benchmark sample are consistent with the DR2 values to within 70 K (root-mean-square error), with most of the remaining scatter due to the \( G_{BP} - G_{RP} \) color’s dependence on metallicity along with \( T_{\text{eff}} \)(see Figure 2 of Morris et al.2018). However, the Apsis \( T_{\text{eff}} \) values diverge from those in our sample for \( T_{\text{eff}} < 4100 \) K.

We also translate our photometric \( T_{\text{eff}} \) values to spectral types (SpT) and stellar masses \( (M_*) \) using the Kraus & Hillenbrand (2007) stellar spectral energy distribution table (their Table 5) to aid the reader’s interpretation of our results. We interpolate mass from \( T_{\text{eff}} \), but only quote the SpT at the nearest \( T_{\text{eff}} \) entry in the Kraus & Hillenbrand (2007) table, which for our sample includes the following spectral types: F5, F8, G0, G2, G5, G8, K0, K2, K4, K5, K7, M0, and M1. Our \( T_{\text{eff}}, M_*, \) and SpT values are listed in Table 1 for all the rotators we identify below and use in our analysis.

2.4. Revisiting the Meibom et al. (2011b) Results

NGC 6811 was observed during the primary Kepler mission. Meibom et al. (2011a) presented rotation periods measured from light curves for Quarters 1–4 for the 71 members they confirmed by RV monitoring.

Two of these stars appear to rotate too slowly in the color–\( P_{\text{rot}} \) plot for NGC 6811: KICs 9595724 and 9717386. These stars are also outliers in the cluster’s DR2 proper motion diagram, and appear too bright in the DR2 CMD, which indicates that they are either not members or are binaries. Either way, they should be removed from the gyrochronology calibration sample.

KIC 9594645 also has a discrepant proper motion (by 1 mas yr\(^{-1}\)), and appears fainter than the cluster’s single-star sequence. Although its \( P_{\text{rot}} \) is consistent with the cluster...
distribution, we reclassify it as a non-single-member and remove it from our sample.

We identified five other photometric binaries in the DR2 CMD (KICs 9594100, 9655310, 9471038, 9775381, and 9592939). While they are consistent with the cluster color–$P_{\text{rot}}$ distribution, that distribution is well populated, and we opted to remove these from the sample.

Figure 2 shows the CMD and color–$P_{\text{rot}}$ diagram for the Meibom et al. (2011a) sample of 71 stars, and highlights the eight stars we identified as non-single-members according to DR2. This leaves 63 stars in the Meibom et al. (2011a) sample with masses 0.79 < $M_\ast$ < 1.29 $M_\odot$ (K2V to F5V).

2.5. Measuring $P_{\text{rot}}$ with Kepler (Again)

We search the Mikulski Archive for Space Telescopes10 for Kepler data for the 278 stars we identify as NGC 6811 members with $(G_{\text{BP}} - G_{\text{RP}}) \gtrsim 0.57$ (the bluest published rotator; Meibom et al. 2011a). We find light curves for 203 stars, 62 of which are redder than the Meibom et al. (2011a) sample. We analyze the pre-search data conditioning simple aperture photometry (PDCSAP; Stumpe et al. 2012; Smith et al. 2012) light curves from Quarters 2-16. Quarters 1 and 17 were truncated and only lasted for 33.47 days and 31.75 days, respectively, whereas the intervening Quarters covered $\approx 90$ days, except for Quarter 8, which lasted for $\approx 67$ days. Most stars have more than one quarter of data.

We compute Lomb–Scargle periodograms (Scargle 1982; Press & Rybicki 1989) for all available quarters for each star (see Figure 3 for an example of our analysis), and report the median and standard deviation values for the resulting $P_{\text{rot}}$ in Table 1. Occasionally, the peak power in the periodogram corresponds to a half-period harmonic (9% of the total number of all $P_{\text{rot}}$ measurements). We automatically detect these cases by identifying outliers with values that when doubled were

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10 https://archive.stsci.edu
within 10% of the median value from all quarters, then correct the measured $P_{\text{rot}}$ by doubling their values.

McQuillan et al. (2014) reported $P_{\text{rot}}$ for 87 of our stars, 57 of which were not identified as members by Meibom et al. (2011a). In Figure 4, we compare the $P_{\text{rot}}$ values we find to those in both Meibom et al. (2011a) and McQuillan et al. (2014), and find close agreement. For McQuillan et al. (2014), we calculate the differences from our periods and find no net offset and a standard deviation of only $\sigma = 0.15$ day.

Finally, there are 11 stars with multiquarter data with large standard deviations; $\sigma P_{\text{rot}} > 1$ day. We discard these from our sample and attribute them to limitations in the data quality or perhaps blending of stars in the Kepler photometric apertures. Our measurements are displayed in a color–$P_{\text{rot}}$ diagram in Figure 5. Table 1 lists the 171 candidate single-star members that now have a measured $P_{\text{rot}}$, and includes 10 stars that are period outliers (they appear too fast or too slow relative to the cluster color–$P_{\text{rot}}$ sequence, which we expect to be fully and tightly converged because the distributions for Praesepe and the Hyades are, as demonstrated by Douglas et al. 2019). KIC 9471304 (one of the outliers) has an ambiguous period measurement and should be treated with skepticism. The remaining 161 rotators more than double the size of the Meibom et al. (2011a) sample and extend it to $\approx 0.6 M_\odot$.

3. Discussion

Below, we calculate the reddening and age for NGC 6811 using gyrochronology. Next, we show that the NGC 6811 K dwarfs have not spun down relative to their cousins in Praesepe, despite their large difference in age. Finally, we present evidence supporting the scenario whereby stars stop spinning down, effectively stalling in their angular-momentum evolution, for an extended period of time.

3.1. A Gyrochronology Reddening and Age for NGC 6811
Using F and G Members

In addition to the $P_{\text{rot}}$ distribution for NGC 6811, Figures 2 and 5 include information on the rotational properties of
these stars to obtain an age for NGC 6811, as long as our gyrochronology model takes Praesepe as its first epoch.

Reddening is an important ingredient in a gyrochronology age calculation. The rapid rise in F dwarf $P_{\text{rot}}$ over the narrow range in $T_{\text{eff}}$ seen in Figure 5 (which corresponds to $0.65 < (G_{\text{BP}} - G_{\text{RP}})_0 < 0.75$, where $(G_{\text{BP}} - G_{\text{RP}})_0$ is the unreddened color; see Figure 6) provides a tight constraint on reddening that is relatively insensitive to age. We fit for reddening by comparing the color–$P_{\text{rot}}$ sequences for Praesepe and NGC 6811. To account for Praesepe’s uncertain age, we remodel the unreddened Praesepe sequence with a sixth-order polynomial, $A_V = 0.035$ and ages $t = 650$ and 700 Myr, and recalculate the braking index relative to the Sun, finding $n = 0.61$ and 0.63 for the two ages.

We project our Praesepe model forward to 1 Gyr, the isochrone age of NGC 6811, and minimize $\chi^2$ between our measured $P_{\text{rot}}$ and the model predictions for the 16 members with $0.65 < (G_{\text{BP}} - G_{\text{RP}})_0 < 0.75$. We repeat this exercise for ages of 0.9 and 1.1 Gyr to constrain the age sensitivity on reddening, and find $A_V = 0.156^{+0.016}_{-0.018}$ and $A_V = 0.145^{+0.006}_{-0.023}$ for $E(B-V) = 0.050^{+0.005}_{-0.006}$ and $E(B-V) = 0.047^{+0.006}_{-0.007}$ for the 650 and 700 Myr cases respectively. The exact ages for Praesepe and NGC 6811 only have a small impact on the resulting reddening, as we illustrate in Figure 6.

Indeed, even adopting an 800 Myr age for Praesepe (Brandt & Huang 2015), the braking index increases to $n = 0.68$, the gyrochronology age for NGC 6811 increases to 1.2 Gyr, but we still find the same reddening value. However, this age is inconsistent with the cluster CMD. A 1.2 Gyr PARSEC isochrone with solar metallicity can only be approximately fit to the cluster turnover by reducing the reddening to zero. This is inconsistent with expectations from the 3D dust map (Green et al. 2018), which has $A_V = 0.25 \pm 0.06$ at the location and distance of NGC 6811. That value is larger than our result. However, if $A_V = 0.25$, we would then infer an age of 1.26 Gyr.

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11 According to models by van Saders & Pinsonneault (2013), metallicity is not expected to significantly impact angular-momentum evolution when period distributions are analyzed with respect to temperature (and therefore color) instead of mass.
with our gyrochronology model, but then a CMD isochrone analysis would demand a significantly younger age of \( \approx 0.95 \) Gyr. The only reddening and age combination that gives a precise and consistent match between isochrone and gyrochronology models with the data is our solution of \( A_V = 0.15 \) and 1 Gyr. We use \( A_V = 0.15 \) for the remainder of this work.

To calculate the cluster age, we consider only G dwarfs with \( 0.75 < (G_{\text{BP}} - G_{\text{RP}}) < 0.90 \) (29 stars within 5500 < \( T_{\text{eff}} \) < 6000 K) by applying \( A_V = 0.15 \). While we do demonstrate in this paper that gyrochronology fails to describe K dwarf spin down, Meibom et al. (2015) showed that gyrochronology does accurately represent G dwarfs at 2.5 Gyr and van Saders et al. (2016) showed that it remains valid up to the age of the Sun. We chose our color cutoff by inspecting where the model diverges from the data in Figure 5, corresponding to \( T_{\text{eff}} \approx 5400 \) K. We find a gyrochronological age of \( t_{\text{gyro}} = 1.04 \pm 0.12 \) Gyr (median and standard deviation) if Praesepe is 670 Myr old (the age derived from an analysis of literature ages by Douglas et al. 2019). Trimming the outliers shown in Figure 5 (two of the cyan stars) reduces the standard deviation to 75 Myr or \( \approx 9\% \), which is incredibly precise. The standard deviation of the mean is only \( \approx 1.5\% \). This gyrochronology age is consistent with the literature isochrone ages (Sandquist et al. 2016; Janes et al. 2013).

As a final test, we solve for reddening and age simultaneously. We minimize \( \chi^2 \) by brute force with both properties as free parameters and find an age of 1.00 Gyr and \( A_V = 0.15 \), consistent with our previous results.

### 3.2. Further Evidence for a Temporary Epoch of Stalled Spin-down for K Stars

The Meibom et al. (2011a) color–\( P_{\text{rot}} \) sequence for NGC 6811 (Figure 2) seems oddly flat compared to that for other clusters and to model expectations: all of the stars less massive than \( M_s \lesssim 1 M_\odot \) appear to have the same \( P_{\text{rot}} \). Meibom et al. (2011a) noted that extrapolating a younger cluster forward in age with the Skumanich Law predicts a different, more sloped shape to this sequence, with lower-mass stars rotating more slowly than their more massive neighbors in color–\( P_{\text{rot}} \) space.

Our work confirms NGC 6811’s departure from expectations, illustrated in Figure 5. The rapid rise in \( P_{\text{rot}} \) from the late-F dwarfs to the early G dwarfs is well represented by the 1 Gyr Praesepe projection. By contrast, the NGC 6811 sequence appears to diverge at redder colors and approach the Praesepe sequence. The natural conclusion is that K dwarfs have a lower braking index.

This challenge to the picture of a color-independent \( n \) is not unexpected: Angus et al. (2015) found that NGC 6811 and Praesepe had color dependencies that were different from each other and from the Hyades and Coma Ber clusters, leading these authors to discard the NGC 6811 and Praesepe samples from their calibration sample. Angus et al. (2015) speculated that these fitting problems could indicate limitations in the gyrochronology formula, and listed metallicity as a possible factor.

Agüeros et al. (2018) suggested an alternative scenario based on the results for NGC 752, whose age of 1.4 Gyr makes it significantly older than NGC 6811 and Praesepe. Agüeros et al. (2018) found that five mid-K dwarfs in the cluster had barely spun down compared to their cousins in Praesepe, while the three late-K/early M dwarfs had not slowed at all.12 Agüeros et al. (2018) hypothesized that stars enter a temporary phase of reduced net braking efficiency, where the stars stop spinning down. Based on where the NGC 6811 and NGC 752 color–\( P_{\text{rot}} \) sequences merged together with Praesepe’s, Agüeros et al. (2018) inferred that the duration of the stalling epoch must depend on mass, and last longer for lower-mass stars.

This work led us to predict that if the color–\( P_{\text{rot}} \) sequence for NGC 6811 were extended to lower masses, it would eventually merge with Praesepe’s. Indeed, as shown in Figure 5, NGC 6811’s deviation away from the 1 Gyr projection continues until \( T_{\text{eff}} \approx 4295 \) K (K6V), where it clearly overlaps with Praesepe. The late-K dwarfs of NGC 6811 have not spun down at all over the \( \approx 350 \) Myr separating the two clusters.

This conclusion is even more striking when data for a younger cluster are included. The left panel of Figure 7 shows \( P_{\text{rot}} \) for the Pleiades (120 Myr; Rebull et al. 2016), Praesepe (Douglas et al. 2017, 2019), and NGC 6811. The Pleiades K dwarfs with \( 4500 < T_{\text{eff}} < 5000 \) K have slowed down appreciably by 670 Myr (stars cooler than 4500 K yet converged on the slow sequence). However, the NGC 6811 stars in this same temperature range have hardly spun down relative to Praesepe, and the late-K/early M dwarfs have not spun down at all, despite their large difference in age.

The right panel of Figure 7 shows gyrochronology ages for individual stars in NGC 6811. While the G dwarfs show that...
the cluster is clearly older than Praesepe (represented by the cyan horizontal line at 670 Myr), this difference in age between NGC 6811 and Praesepe appears to vanish at $T_{\text{eff}} \lesssim 4700$ K.

### 3.3. Validating the Stalled Braking Scenario with Kepler

While in models $n$ is generally taken to be independent of color and constant in time (e.g., Barnes 2007), data like those presented in Figure 5 have been used to suggest that K dwarfs spin down more gradually than their more massive siblings. For example, comparing the $P_{\text{rot}}$ sequences of M34 and NGC 6811 to that for the Hyades led Meibom et al. (2011a, 2011b) to suggest that $n$ depends on color and is smaller for redder/cooler stars.

We test this hypothesis by calculating a color-dependent braking index using our data for NGC 6811 and our empirical fit to Praesepe: if $P_{\text{rot}} \propto T^n$, then $n = \log(P_{\text{rot}, 2}/P_{\text{rot}, 1})/\log(t_2/t_1)$. We adopt ages for Praesepe and NGC 6811 of 670 Myr and 1 Gyr, and $A_V = 0.035$ and 0.15, respectively. The resulting dependence of $n$ on DR2 color is shown in Figure 8. By eye, it seems that $n$ is constant for $(G_{\text{BP}} - G_{\text{RP}})_0 < 0.9$, after which it drops down toward 0.

It appears that the NGC 6811 data support a reduced braking efficiency for K dwarfs. However, this explanation cannot be correct, as we show by testing this model with the Kepler $P_{\text{rot}}$ distribution for field stars (McQuillan et al. 2014). We propagate the Praesepe color-$P_{\text{rot}}$ sequence forward in time, assuming a color-dependent $n$, and compare the results to the observed distribution of $P_{\text{rot}}$. The bottom panel of Figure 8 shows the Kepler $P_{\text{rot}}$ as a function of $T_{\text{eff}}$, along with the fit for Praesepe and the prediction for the approximate age of the universe, 13.7 Gyr. According to this model, the universe is not old enough for the K dwarfs in the Kepler field to have spun down to their observed $P_{\text{rot}} \approx 30$–40 days.

We therefore interpret the data in the left panel of Figure 7 differently. Following the Agüeros et al. (2018) hypothesis, we argue that spin down stalls after stars converge on the slow sequence for some amount of time, after which stars resume braking as expected with a common $n$. The shape of the curve in the right panel of Figure 7 reveals how the duration of stalling increases toward lower masses and cooler $T_{\text{eff}}$.

### 4. Conclusions

Prior to this work, the sample of rotators in the 1 Gyr-old cluster NGC 6811 was limited to 71 RV-confirmed members with masses $\gtrsim 0.8 M_\odot$. Fortunately, many more candidate members were targeted for observation for the Kepler Cluster Study (Meibom et al. 2011a).

We used data from Gaia DR2 to identify hundreds more likely single members with Kepler light curves, and we measured rotation periods for 171 of them. This more than doubles the size of the rotator sample for this cluster, and importantly extends it down to $M_\star \approx 0.6 M_\odot$, covering the full K dwarf range.

Focusing on the G dwarfs, for which we expect the Skumanich Law to be valid at least up to the age of the Sun (van Saders et al. 2016), we find an extremely precise gyrochronological age of $t_{\text{gyro}} = 1.04 \pm 0.07$ Gyr (median and standard deviation of 27 G-type stars), relative to the 670 Myr-old benchmark Praesepe (i.e., $\approx 1.5 \times$ older). However, this difference in age appears to vanish for stars cooler than $T_{\text{eff}} < 4800$ K.

This could be interpreted as evidence for a mass-dependent braking index $n$, resulting in K dwarfs spinning down much more slowly than F and G dwarfs. However, this scenario cannot reproduce the distribution of $P_{\text{rot}} \approx 30$–40 days observed for these stars in the Kepler field by McQuillan et al. (2014)—the universe is not old enough for K dwarfs to spin down to these $P_{\text{rot}}$ under this model.

Instead, we argue that K dwarfs stop spinning down after converging on the slow sequence at some time prior to the age of Praesepe. Braking stalls for an extended period of time, the duration of which increases toward lower masses/cooler temperatures. At some age older than NGC 6811 (1 Gyr) or NGC 752 (1.4 Gyr), the braking efficiency increases to a Skumanich-like value, and the stars resume spinning down.

What might be causing this epoch of stalled braking? The cluster data demonstrate that the net angular-momentum loss is low during this phase compared to the time before and following it. If this is the case, then either the braking torque is temporarily reduced, and/or the photosphere is gaining angular momentum from the interior to offset that lost via magnetic
We propose that measurements of rotation in an even older cluster, for example, Ruprecht 147 (2.5 Gyr; Torres et al. 2018; Curtis 2016; Curtis et al. 2013), will show that the K dwarfs resume spinning down more efficiently after the age of NGC 6811 or NGC 752, and we expect that the braking index that is found will be consistent with the distribution of $P_{\text{rot}}$ observed in the Kepler field.

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Facilities: Gaia, Kepler.

software: The IDL Astronomy User’s Library (Landsman 1993).

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13 https://www.cosmos.esa.int/gaia
14 https://www.cosmos.esa.int/web/gaia/dpac/consortium

braking (e.g., Bouvier 2008; Denissenkov et al. 2010; Hartman et al. 2010; Gallet & Bouvier 2013, 2015; Lanzafame & Spada 2015).

Denissenkov et al. (2010) discuss a core–envelope decoupling model, and quote a timescale of $\tau_{c-e} = 55 \pm 25 \text{ Myr}$ and $175 \pm 25 \text{ Myr}$ for 1.0 $M_\odot$ and 0.8 $M_\odot$ stars ($T_{\text{eff}} \approx 4850 \text{ K, K2}$). This K dwarf timescale does not seem long enough to address the spin-down discrepancy we see between NGC 6811 and Praesepe. Gallet & Bouvier (2015) quote values of $\tau_{c-e} = 150–500 \text{ Myr}$ for 0.5 $M_\odot$ stars, but their slowest track is only $\approx 70\%$ the period of Praesepe’s converged slow sequence, so modeling challenges persist. We are eager to see these theoretical models recalibrated with our new rotator sample for NGC 6811.
