K2 Rotation Periods for Low-mass Hyads and a Quantitative Comparison of the Distribution of Slow Rotators in the Hyades and Praesepe

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Abstract

We analyze K2 light curves for 132 low-mass (1 M⊙ ≳ M ≳ 0.1 M⊙) members of the 600–800 Myr old Hyades cluster and measure rotation periods (P_rot) for 116 of these stars. These include 93 stars with no prior P_rot measurements; the total number of Hyads with a known P_rot is now 232. We then combine literature binary data with Gaia DR2 photometry and astrometry to select single-star sequences in the Hyades and its roughly coeval Praesepe open cluster and derive a new reddening value of A_V = 0.035 ± 0.011 for Praesepe. Comparing the effective temperature–P_rot distributions for the Hyades and Praesepe, we find that solar-type Hyads rotate, on average, 0.4 day slower than their Praesepe counterparts. This P_rot difference indicates that the Hyades is slightly older than Praesepe: we apply a new gyrochronology model tuned with Praesepe and the Sun and find an age difference between the two clusters of 57 Myr. However, this P_rot difference decreases and eventually disappears for lower-mass stars. This provides further evidence for stalling in the rotational evolution of these stars and highlights the need for more detailed analysis of angular momentum evolution for stars of different masses and ages.

Key words: open clusters and associations: individual (Hyades, Praesepe) – stars: evolution – stars: late-type – stars: rotation

Supporting material: figure set, machine-readable tables

1. Introduction

The Hyades and Praesepe open clusters are benchmarks for determining the dependence of stellar rotation on age. The Hyades was one of the first open clusters for which photometric rotation periods (P_rot) were measured for low-mass stars (<1 M⊙; Radick et al. 1987, 1995). The two clusters are sufficiently nearby such that many photometric P_rot across the full FGKM mass range have now been measured from both ground- and space-based photometric monitoring (e.g., Agüeros et al. 2011; Delorme et al. 2011; Hartman et al. 2011; Douglas et al. 2014, 2016, 2017; Rebull et al. 2017).

Empirical efforts to establish the functional form of the rotation–age relation, sometimes referred to as gyrochronology (Barnes 2003), have commonly assumed that the mass dependence can be separated from the age dependence, such that P_rot(M, t) = f(M) × g(t). This was famously proposed by Skumanich (1972), who found that solar-type stars spin down as P_rot ∝ t^n, where the braking index n ≈ 0.5. Barnes (2003, 2007) accounted for the dependence on mass by adopting photometric color as its observational proxy, then fit coefficients for a simple analytic function from observations of rotators with a range of masses in young nearby clusters. The resulting model implied that lower-mass stars spin down more rapidly than their solar-type counterparts. Later authors (e.g., Mamajek & Hillenbrand 2008; Meibom et al. 2009; Angus et al. 2015) adjusted the coefficients and braking index but otherwise assumed the same functional form as Barnes. However, an examination of the figures in Barnes (2003) shows that this fixed relation between P_rot, t, and color is insufficient to describe stellar spin-down for stars with a range of masses.

More recent P_rot measurements for G and K dwarfs in open clusters have shown that P_rot evolution cannot be described by separating the mass and age dependence. Using the Skumanich relation, Meibom et al. (2011a) tested whether Hyades rotators could be spun up to match the observed distribution of P_rot in M34, which is 220 Myr old. These authors determined that while the distribution of spun-up solar-type Hyades did match that of their younger cousins, spinning up Hyades K dwarfs by the same factor resulted in these stars having faster P_rot than those observed in M34. Comparing the P_rot measured for GKM stars in various open clusters from 100 Myr to 1 Gyr leads to a similar conclusion: Skumanich-like spin-down works well for solar-type stars, but K dwarfs spin down more slowly (Meibom et al. 2011a; Cargile et al. 2014; Agüeros et al. 2018).

Furthermore, while retuning the coefficients for the Barnes (2007) gyrochronology equation, Angus et al. (2015) could not simultaneously fit Praesepe and the Hyades. When including Praesepe, these authors’ fit resulted in a multimodal distribution for their color singularity term, which controls the downturn toward rapid rotation for bluer/hotter/more massive stars (which have thinner convective envelopes, resulting in relatively weaker magnetic dynamos and braking efficiency). This is additional evidence that the shape of the slow-rotator sequence can vary from cluster to cluster.

A complication in using the Hyades and Praesepe for calibrating gyrochronology is that their absolute and relative
Finally, we derive single-star sequences in both clusters using the second Gaia data release (DR2; Gaia Collaboration et al. 2018b), obtain a new reddening value for Praesepe, and derive a differential gyrorochnological age for the Hyades in Section 6. We discuss our results and their potential implications for calibrating angular momentum evolution in Section 7 and conclude in Section 8.

2. Existing Data

2.1. Hyades Membership and Rotation Catalog

As in Douglas et al. (2014, 2016), we use the Röser et al. (2011) and Goldman et al. (2013) catalogs as the basis for our work. To these, we add 13 stars identified using reduced proper motions and parallaxes from Hipparcos, bringing us to 786 total Hyads. Since archival data for the Hyades are generally of high quality, and since our pre-Gaia catalog was used to select our two Campaigns and 13 targets (Guest Observer proposals 4095 and 13064), we do not attempt to update the full cluster membership list using Gaia DR2.

Furthermore, since our sample consists of variable stars and includes probable binaries, these stars will have increased photometric variability and possibly also high astrometric excess noise. This variability and excess noise will impact the availability of the Gaia data, as well as the determination of appropriate quality cuts. Indeed, 188 stars in our original catalog do not pass the quality cuts recommended by the Gaia Collaboration et al. (2018a), and >80 of these are confirmed or candidate binaries.

In Douglas et al. (2014, 2016), we assembled $P_{\text{rot}}$ measurements for Hyads from Radick et al. (1987, 1995), Prosser et al. (1995), Delorme et al. (2011), Hartman et al. (2011), and an analysis of All Sky Automated Survey (ASAS; Pojmański 2002) data (A. Kundert & P. Cargile 2014, private communication) into a catalog of 102 rotators. We then added 37 new $P_{\text{rot}}$ from our analysis of Campaign 4 data in Douglas et al. (2016), bringing the total number of known Hyades rotators to 139. With a few exceptions, these surveys generally measure consistent $P_{\text{rot}}$; for details, see Douglas et al. (2014, 2016). The mass–period relationship for these 139 Hyads is shown in Figure 1.

In the second half of this paper, we consider only single, slowly rotating Hyads, and we use Gaia data to select these stars. We match our Douglas et al. (2016) Hyades catalog to Gaia DR2 and select the nearest neighbor. We then check this match by computing synthetic Gaia $G$ magnitudes from UCAC $r, i$ magnitudes (Zacharias et al. 2010), SDSS $r, i$ (Alam et al. 2015), Two Micron All Sky Survey (2MASS) $J, K$ (Skrutskie et al. 2006), and/or Tycho2 $B, V$ (as given in 2MASS). We require that at least one of these synthetic magnitudes match the measured Gaia $G$ value to within one standard deviation ($\sigma$) for optical photometry or $2\sigma$ for 2MASS photometry. Of the 786 stars in our catalog, only 10 fail this test: three stars lack photometry to compute synthetic $G$ magnitudes, two lack Gaia

In Douglas et al. (2014), we cited these $P_{\text{rot}}$ as A. Kundert et al., and in Douglas et al. (2016), we cited them as P. Cargile et al. These periods were measured by A. Kundert as an undergraduate while being supervised by coauthor P. Cargile. The paper was never completed, however, and additional ASAS data have become available for Hyades members in the last few years. We therefore give the existing ASAS $P_{\text{rot}}$ measurements in Table 3, but further details will be provided in a later paper, where we will reanalyze the expanded ASAS data set.

| Stars & Notes | $P_{\text{rot}}$ (Myr) | $P_{\text{rot}}$ (Myr) |
|-------------|----------------|----------------|
| Perryman et al. (1998) | 625 ± 50 | ... |
| Fossati et al. (2008) | ... | 590 ± 250 |
| Brandt & Huang (2015a) | 750 ± 100 | ... |
| Brandt & Huang (2015b) | 790 ± 60 | 790 ± 60 |
| David & Hillenbrand (2015) | 827 ± 10 | ... |
| ... | 764 ± 10 | ... |
| Cummings et al. (2017) | 635 ± 25 | 670 ± 25 |
| Cummings et al. (2018) | 705 ± 25 | 700 ± 25 |
| Gossage et al. (2018) | 676 ± 11 | 617 ± 10 |
| ... | 741 ± 15 | 617 ± 15 |
| ... | 676 ± 13 | 689 ± 13 |
| ... | 589 ± 12 | 617 ± 12 |
| Gaia Collaboration et al. (2018a) | 794 | 708 |

Notes:  
* David & Hillenbrand (2015) fit two different isochrone models; we give both results from their summed PDF analysis in log age space.  
* Cummings et al. (2018) fit two different isochrone models; we list both results.  
* Gossage et al. (2018) fit models with different rotation parameterizations to both ($B, V$) and ($J, K_s$) photometry. We give the results from fitting the model with a free rotation parameter and the model with a fixed rotation parameter but a spread in rotation to both CMDs.
counterparts, and five fail the G-magnitude test. However, none of those 10 stars have a measured $P_{\text{rot}}$ or are K2 targets, so they do not impact our analysis and are excluded from all tables.

2.2. Praesepe Membership and Rotation Catalog

We continue to use the Douglas et al. (2017) Praesepe membership catalog, which is based primarily on Kraus & Hillenbrand (2007). Our catalog includes 1130 cluster members with $P_{\text{mem}} \geq 50\%$ from Kraus & Hillenbrand (2007), supplemented by 39 previously cataloged members too bright to be identified by those authors. We assign these bright stars $P_{\text{mem}} = 100\%$.

In Douglas et al. (2014, 2017), we gathered $P_{\text{rot}}$ measurements for Praesepe members from Agüeros et al. (2011), Delorme et al. (2011), Kovács et al. (2014), Scholz & Eislöffel (2007) and Scholz et al. (2011). We combined these literature values with 677 $P_{\text{rot}}$ derived from our K2 Campaign 5 data; in total, our catalog includes $P_{\text{rot}}$ data for 743 Praesepe members.

We match this list of Praesepe rotators to Gaia DR2 and again select the nearest neighbor. Only three rotators in our catalog lack a DR2 match within 0′1: EPIC 211970974 and EPIC 211907026 are both rapidly rotating M dwarfs, and EPIC 211954582 is overluminous by −1.18 mag, which suggests that it might be a triple system. Since our analysis focuses on single, slowly rotating stars, the lack of a DR2 match in these three cases does not affect this work.

Five additional stars were mismatched when searching for the nearest neighbor, but in each case, another star was found within 0′1 with photometry consistent with our target: Gaia DR2 661314466963687808 (EPIC 211971468), Gaia DR2 659680072990872704 (EPIC 211903302), Gaia DR2 661355934869899648 (EPIC 211983811), Gaia DR2 663055371825360000 (EPIC 211981509), and Gaia DR2 661312267940341632 (EPIC 211966619).

3. Derived Stellar Properties

3.1. Stellar Masses

As in previous work, we estimate stellar masses by linearly interpolating between the $M_K$ and $M_*$ points given by Kraus & Hillenbrand (2007), who listed $M_*$ and spectral energy distributions (SEDs) for B8–L0 stars.

We calculate distances ($D$) to individual stars using Gaia DR2 or Hipparcos (Perryman et al. 1998) parallaxes or the secular parallaxes from Röser et al. (2011) or Goldman et al. (2013). For stars passing the Gaia quality cuts, we use Gaia parallaxes. For the remaining stars, we use Hipparcos or secular parallaxes. We then use these distances to compute $M_K$.

We also propagate the $m_K$ and $D$ uncertainties for each star to determine the $M_*$ uncertainties, $\sigma_{M_*}$. The uncertainties are typically small, on the order of a few percent. In our previous work, a few stars had large uncertainties in $D$, which led to large mass uncertainties. The improved parallaxes from Gaia have remedied this. Our stated $\sigma_{M_*}$ are only the systematic uncertainties resulting from our calculation and the chosen model; they do not take into account other sources of uncertainty, such as our choice of model or K-band excesses due to a binary companion.

3.2. Effective Temperatures

In Section 6, we also compare the two clusters’ $P_{\text{rot}}$–$T_{\text{eff}}$ relations. For solar-type stars with 4700 K < $T_{\text{eff}}$ < 6700 K, we derive an empirical color–$T_{\text{eff}}$ relation using a Gaia DR2 match to the California Planet Survey catalog (Brewer et al. 2016). For warmer stars, we supplement this with Hyades members from Gaia Collaboration et al. (2018) with $T_{\text{eff}}$ from DR2/Apsis (Andrae et al. 2018). For cooler stars, we combine the benchmark K and M dwarfs from Mann et al. (2015) and Boyajian et al. (2012). That sample only reaches $T_{\text{eff}}$ > 3056 K, so we also adopt the Rabus et al. (2019) $M_K$–$T_{\text{eff}}$ relation for stars with 2600 K < $T_{\text{eff}}$ < 4000 K. At $T_{\text{eff}}$ = 4000 K, our color–$T_{\text{eff}}$ relation predicts a value only 9 K different from the Rabus et al. (2019) formula when using our fit to the Hyades main sequence to convert between color and absolute magnitude.

4. Binary Identification

We search for binaries among known rotators in the Hyades because they can bias our analysis of the $P_{\text{rot}}$ distribution. Binary companions may exert tidal or other physical effects on the primary star (e.g., Meibom & Mathieu 2005; Meibom et al. 2007; Zahn 2008; Douglas et al. 2016, 2017). In addition, when two (or more) stars are blended in a given image, the second star may dilute the rotational signal and/or add flux that will cause us to overestimate $L_{\text{bol}}$ and $M_*$. These effects can cause stars to be misplaced in the mass–period plane, leading us to misidentify trends or transitions in the period distribution. Finally, short-period binaries are susceptible to tidal interactions, which can cause atypical angular momentum evolution. Binaries with orbital periods under ~10 days might be circularized and locked, but others with orbital periods up to 30 days could still be affected. We therefore wish to identify as many binary systems as possible among our Hyades K2 targets. We denote all confirmed and candidate binaries in our analysis.
and provide a brief overview of our binary identification methods below. For more details, see Douglas et al. (2016, 2017).

1. **Visual identification.** We examine a coadded K2 image, a Digital Sky Survey (DSS) red image, and a 2MASS (Cutri et al. 2003) K-band image of each target to look for neighboring stars (see Figure 4). We use a flag of “Y” for yes, “M” for maybe, and “N” for no to indicate whether the target and a neighbor have blended point-spread functions (PSFs) on the K2 chip. Stars flagged as “Y” are labeled candidate binaries; we find 38 such targets, or 29% of stars with K2 P\textsubscript{rot}.

By searching 12 regions of the nearby sky in Gaia DR2, we find the rate of chance alignments with G \leq 20 mag stars within 10" to be \approx 6\%–58\%. We find a range in potential contamination rates because the Hyades is so large on the sky: part of the cluster sits close
to the Galactic plane, but it also extends well away from the plane. At typical Hyades distances, 106 corresponds to ≈400–550 au; it is possible that all of the blends we identify are chance alignments or that up to 23% of Hyads have a companion within ≈400–550 au (for comparison, we determined that ≈10% of Praesepe members likely have a bound companion within 106, or 106–107 au; Douglas et al. 2017). For consistency with our previous work, we continue to label probable blends as candidate binaries.

2. Photometric identification. As in previous work, we identify candidate unresolved binaries that are over-luminous for their color. In Douglas et al. (2014, 2016, 2017), we selected binaries that were over-luminous in an r′ versus (r′ − Ks) color–magnitude diagram (CMD) using Hipparcos (Perryman et al. 1998) parallaxes or secular parallaxes from Röser et al. (2011) and Goldman et al. (2013). As in Section 3.1, we now update the r′ versus (r′ − Ks) selection using Gaia DR2 parallaxes when the data pass the quality cuts defined in Gaia Collaboration et al. (2018a). We also select new photometric candidate binaries using Gaia DR2 photometry, discussed further in Section 6.1.2. This method is biased toward binaries with equal masses, and we are certainly missing candidate binaries with lower mass ratios. Our binary selections are shown in Figure 2; in Section 5 we flag all photometric candidate binaries, but in Section 6 we reject only candidates selected from Gaia photometry.

3. Multiperiodic K2 stars. In binaries where the components have roughly equal brightness, variability from both stars can appear in the K2 light curve. However, we may also detect two $P_{\text{rot}}$ and/or an obvious beat pattern when a single star exhibits differential rotation. As discussed in Section 5, we assume that the two periods come from different components of a binary if the periods are different by >20%. This cutoff is based on the maximum period separation for differentially rotating spot groups on the Sun. We find multiple $P_{\text{rot}}$, indicating probable unresolved binaries, in 11 K2 targets.

4. Literature identifications. We searched the literature for Hyades binaries among known rotators and K2 Campaign 4 targets in Douglas et al. (2016). We update this list with binaries among our Campaign 13 targets. We also add binaries identified or confirmed through observations with the Tillinghast Reflector Echelle Spectrograph on the 1.5 m Tillinghast telescope at the Smithsonian Astrophysical Observatory’s Fred L. Whipple Observatory on Mt. Hopkins, Arizona (R. Stefanik 2018, private communication).

We consider all visual and photometric pairs, as well as multiperiodic K2 stars, to be candidate binaries in our analysis. For other literature binaries, we follow the confirmed versus candidate nomenclature used in the source paper. The resulting list of confirmed and candidate binaries is given in Table 2.

5. Measuring New Hyades Rotation Periods with K2

5.1. K2 Data and Initial $P_{\text{rot}}$ Measurement

During its Campaign 13, which lasted from 2017 March 8 to May 27, K2 targeted the Hyades for a second time. We analyze the resulting long-cadence data for 132 Hyads identified in Section 2.1 and with Kepler magnitudes $K_p > 9$ mag and $M_K < 1.5 M_\odot$. These limits exclude saturated stars, as well as stars with radiative outer layers, which are outside of the scope of this work. The distribution of Hyades targets in K2 Campaigns 4 and 13 is shown in Figure 3.

We use detrended light curves generated using the K2 systematics correction method (K2SC; Aigrain et al. 2016) for our analysis. Aigrain et al. (2016) developed a semiparametric Gaussian process model to simultaneously correct for the spacecraft motion and model the stellar variability. As discussed in Douglas et al. (2017), we find that this approach is best at removing instrumental signals and trends while leaving stellar periodic signals intact. We ran the K2SC code on the K2 PDC pipeline light curves ourselves, since the processed K2SC light curves for Campaign 13 are not yet on MAST. We downloaded the pipeline light curves in 2018 March.

We follow the same period measurement method used in Douglas et al. (2017) and only summarize it here. We use the Press & Rybicki (1989) FFT-based Lomb–Scargle algorithm\footnote{For more information, see Aigrain et al. (2016) and the MAST high-level science product page, https://archive.stsci.edu/prepds/k2sc/} to measure $P_{\text{rot}}$. We compute the Lomb–Scargle periodogram power for $3 \times 10^5$ periods ranging from 0.1 to 70 days (approximately the length of the campaign). We also compute minimum significance thresholds for the periodogram peaks using bootstrap resampling and only consider a peak to be significant if its power is greater than the minimum significance threshold for that light curve. We take the highest significant peak as our default $P_{\text{rot}}$ value; only three of our targets show no significant periodogram peaks.
### Table 2

Confirmed and Candidate Multiple Systems among the K2 Targets and Hyads with Measured $P_{\text{rot}}$

| [RSP2011]$^a$ | HIP   | 2MASS          | EPIC | D16 Cand.? | Updated Cand.? | Gaia Cand.? | Conf.? | References                                                                 |
|-------------|--------|----------------|------|------------|----------------|--------------|--------|----------------------------------------------------------------------------|
| 323         | …      | 04260584 +1531275 | …    | N          | N              | N            | Y      | Patience et al. (1998); R. Stefanik (2019, private communication)           |
| 293         | HIP 20577 | 04242831 +1653103 | …    | Y          | Y              | N            | Y      | Douglas et al. (2014), Patience et al. (1998), Kopytova et al. (2016)       |
| 360         | HIP 20899 | 04284827 +1717079 | …    | N          | N              | N            | Y      | Mason et al. (2001)                                                        |
| 329         | HIP 20719 | 04262460 +1651118 | …    | Y          | Y              | N            | N      | Douglas et al. (2014), Mermilliod et al. (2009)                            |
| 330         | HIP 20741 | 04264010 +1644488 | …    | N          | N              | N            | Y      | Morzinski (2011)                                                           |
| 330         | HIP 22030 | 04463036 +1528194 | …    | N          | N              | N            | Y      | Morzinski (2011), R. Stefanik (2019, private communication)                 |

**Note.**

$^a$ Index in the Röser et al. (2011) catalog.

(This table is available in its entirety in machine-readable form.)
5.2. Period Validation

We employ several automated and by-eye quality checks to validate the $P_{\text{rot}}$ identified above. We inspect each phase-folded light curve to confirm that the detected $P_{\text{rot}}$ appears astrophysical and not instrumental. Clearly spurious detections are flagged as $Q = 2$ and questionable detections as $Q = 1$. A $Q = 3$ flag indicates that there were no significant periodogram peaks. Figure 3 in Douglas et al. (2017) shows examples of various light-curve features and describes how we flag them.

We also plot the full light curve with vertical dashed lines at intervals corresponding to the detected $P_{\text{rot}}$ to ensure that the light-curve features repeat over several intervals. Finally, we

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Figure 4. An example of the plots used to inspect period detections and check for neighboring stars. Left column, top to bottom: K2 pixel stamp with DSS red image overlaid as a contour, DSS red image rotated into the K2 frame, 2MASS image rotated into the K2 frame, and the target’s position within the K2 Campaign 13 field of view. A faint companion is visible in both the DSS and 2MASS images. Right column, top to bottom: Lomb–Scargle periodogram with (up to) the three highest significant peaks indicated by inverted triangles, the light curve corrected for spacecraft drift, the white-noise component of the light curve, the time-dependent component, and the light curve phase-folded on (up to) the three most significant periods. The colors of the markers indicating the peaks in the periodogram correspond to the colors of the phase-folded light curves. Slight spot evolution is apparent, and the K2SC algorithm struggles around the middle of the campaign. Versions of this plot for every K2 target analyzed are available in the figure set. (The complete figure set (132 images) is available).
check for cases where there is a double dip in the light curve, and the highest periodogram peak likely corresponds to half of the true $P_{\text{rot}}$. This is caused by two similar spot groups on opposite sides of the star. We then select the correct peak as the final $P_{\text{rot}}$.

Figure 4 shows an example of the plots we use to inspect the data; we include a figure set showing these plots for every target in our sample online.

We find 13 stars with significant periodogram peaks but no believable $P_{\text{rot}}$. In six cases, the light curve is just noise or displays only a long trend, without any detected periodic variability. In the remaining seven cases, there is some probable spot-induced variability, but the phase-folded light curves do not actually match up, and there is no clear period. In these cases, we are likely observing rapid spot evolution, perhaps on two stars in a binary.

For 18 other stars, the highest periodogram peak does not appear to correspond to the true $P_{\text{rot}}$. In some cases, as above, the highest periodogram peak comes from a campaign-long trend, and the true period is detected at a weaker power. In other cases, we find a double-dip light curve with almost no difference between the central (half-period) dip and the primary (full-period) dip. In these cases, the phase-folded light curve for the longer period shows the double-dip pattern clearly, even though it is detected at a lower periodogram power.

EPIC 210741091 and EPIC 247337843 are two very interesting cases: it is hard to define a period because the spot modulation only appears in half the campaign. For EPIC 210741091, there is initially some variability but no clear periodic signal; a V-shaped dip suggesting a single large spot (Bopp & Evans 1973; Eker 1994) appears about halfway through the campaign. Nonetheless, we measure $P_{\text{rot}} = 11.78$ days for this star, very close to the $P_{\text{rot}} = 11.98$ days we measured in Campaign 4. EPIC 247337843 develops rapidly from cycle to cycle, from a slight double dip at the beginning of the campaign to variability with no clear period by the second half. Given this variability and partial lack of signal for both stars, we assign $Q = 1$ for their Campaign 13 $P_{\text{rot}}$.

Finally, in 11 light curves we detect two signals with periods differing by at least 20%. We consider these stars to be candidate binaries. Several other stars exhibit two close but distinct periodogram peaks, and the light curves have obvious beat patterns. This suggests that in these cases, we are observing differential rotation of two spot groups at different latitudes.

5.3. Summary: New K2 Periods for the Hyades

We obtain robust $P_{\text{rot}}$ measurements for 116 Hyades members, including 93 members with no prior $P_{\text{rot}}$ measurement. The vast majority of these periods are for rapidly rotating M dwarfs and bring the total number of Hyads with $P_{\text{rot}}$ to 232. Our $P_{\text{rot}}$ values, flags, and analysis outputs are found in Table 3. Our new rotation periods, along with literature values, are shown as a function of stellar mass in Figure 5.

Only 23 stars have $P_{\text{rot}}$ measured here and in previous studies, including five with a $P_{\text{rot}}$ measurement from K2 Campaign 4 (Douglas et al. 2016). Figure 6 shows a comparison of the existing data with our new measurements. In two cases (EPIC 210554781 and EPIC 246806983), the literature period is also detected as a secondary period in the K2 light curve. In two other cases (EPIC 210558541 and EPIC 246714118), we detect a short $P_{\text{rot}}$ in K2 and do not detect the longer literature $P_{\text{rot}}$ at all. In general, however, we find that ground- and space-based $P_{\text{rot}}$ measurements agree to within 10%, similar to our results in Praesepe (Douglas et al. 2017).
Table 3

\( P_{\text{rot}} \) Measurements for Hyades Stars Targeted in \( K2 \) and in the Literature

| [RSP2011]\(^a\) | EPIC | \( P_{\text{rot,1}} \) (days) | \( Q_1 \)\(^b\) | \( P_{\text{rot,2}} \) (days) | \( Q_2 \)\(^b\) | Multi\(^c\) | Blend\(^d\) | \( P \) | Radick \( P_{\text{rot}} \) (days) | Prosser \( P_{\text{rot}} \) (days) | HATnet \( P_{\text{rot}} \) (days) | SWASP \( P_{\text{rot}} \) (days) | ASAS \( P_{\text{rot}} \) (days) | \( K2 \) \( P_{\text{rot}} \) (days) |
|-----------------|------|-----------------|---------|-----------------|---------|---------|---------|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 549             | 248045685 | 40.10 | 2       | ...           | ...    | N       | N       | ...   | ...             | ...             | ...             | ...             | ...             | ...             | ...             |
| 544             | 247611242 | 11.79 | 0       | ...           | ...    | N       | Y       | 3     | ...             | ...             | ...             | ...             | 12.69           | 13.59           | ...             |
| 428             | 247369717 | 11.83 | 1       | ...           | ...    | M       | N       | K     | ...             | ...             | ...             | ...             | 11.98           | ...             | ...             |
| 571             | 246865157 | 12.22 | 0       | ...           | ...    | N       | N       | D     | ...             | ...             | ...             | ...             | 10.77           | ...             | ...             |
| 362             | 210554781 | 11.51 | 0       | 3.60          | 0      | Y       | N       | R     | 3.66            | ...             | ...             | ...             | ...             | ...             | ...             |
| 409             | 246777832 | 12.90 | 0       | ...           | ...    | N       | N       | D     | ...             | ...             | ...             | ...             | 13.13           | ...             | ...             |
| 553             | 246931087 | 10.81 | 0       | ...           | ...    | N       | Y       | D     | ...             | ...             | ...             | ...             | ...             | 13.14           | ...             |
| 587             | 246732310 | 12.90 | 0       | ...           | ...    | N       | Y       | Y     | ...             | ...             | ...             | ...             | 14.94           | ...             | ...             |
| 355             | 210651981 | 2.45  | 0       | 1.07          | 1      | M       | Y       | 2     | 2.42            | ...             | 2.42            | ...             | 2.44            | ...             | ...             |
| 658             | 246806983 | 2.61  | 0       | 14.31         | 1      | Y       | N       | D     | ...             | ...             | ...             | 14.94           | ...             | ...             | ...             |

Notes.

\(^a\) Index in the Röser et al. (2011) catalog.

\(^b\) Quality of the \( P_{\text{rot}} \) detection, where 0 is a high-confidence measurement, 1 is questionable, 2 is not trusted, and 3 indicates that there were no significant periodogram peaks.

\(^c\) Presence of multiple periods in the light curve. Here Y, M, and N represent “yes,” “maybe,” and “no,” respectively.

\(^d\) Presence of a blended neighbor. Here Y, M, and N represent “yes,” “maybe,” and “no,” respectively.

\(^e\) Flag for the \( P_{\text{rot}} \) source selected: “R,” Radick et al. (1987, 1995); “P,” Prosser et al. (1995); “H,” Hartman et al. (2011; HATnet); “D,” Delorme et al. (2011; SWASP); “A,” ASAS; “2,” Douglas et al. (2016; K2 Campaign 4); and “3,” this work (K2 Campaign 13).

(This table is available in its entirety in machine-readable form.)
Based on the similarity of their CMDs and their activity, rotation, and lithium abundance data, the Hyades and Praesepe are often assumed to be coeval clusters (e.g., Douglas et al. 2014; Cummings et al. 2017). Here we test this assumption using our expanded rotator samples paired with the high-precision data from Gaia DR2 for each cluster. First, we identify likely single-star members of each cluster. Then, we apply a new gyrochronology model tuned with the Praesepe’s rotation and lithium abundance data to infer a precise, relative, gyrochronological age for the Hyades.

6.1. Defining Single-star Sequences

A comparison of our Figure 5 and Figure 7 in Douglas et al. (2017) shows that the color–rotation distributions for the Hyades and Praesepe appear qualitatively similar to each other. Most stars follow a common slow-rotator sequence from the late-F stars down to early M, followed by a sharp transition from slow-rotating sequence and the Sun to infer a precise, relative, gyrochronological age for the Hyades.
to rapid near the fully convective boundary at \( \approx M_4 \). However, many stars are outliers and appear to be rotating more rapidly or slowly than the slow-rotating sequence.

Where possible, it is important to reject outliers following membership and multiplicity criteria, instead of removing them based on their position in color–period space. The primary reason is that we wish to show that \( \approx 700 \) Myr old stars follow a single-valued color–\( P_{\text{rot}} \) relation from mid-F down to early M, and that any rapid stars in this mass range are rapid for a reason unrelated to single-star angular momentum evolution (e.g., because they are binaries, blends, or interlopers or have poor data). Since the Hyades and Praesepe samples of rotators are large, we can apply strict physical (e.g., based on positions, kinematics, or luminosity excesses) and data quality criteria (e.g., poor astrometric solutions, blended light curves resulting in multiple period detections) to select stars with Kepler and Gaia data consistent with single-star membership without overdepleting the color–period plane at any color. We describe our selection criteria below; each criterion is applied independently and the outputs combined to create our final list of single members. The results are summarized in Figure 7, and Tables 3 and 4 include flags indicating which tests were passed by each star.

### 6.1.1. Kinematics

For the Hyades, we select candidate single stars first by rejecting confirmed binaries identified in the literature and then by considering the Galactic \( UVW \) space velocities for stars with six-parameter positions and kinematics from Gaia DR2. We calculate the cluster median \( UVW \) velocities from the Hyades membership list in Gaia Collaboration et al. (2018a). If next, we compute the absolute velocity deviation, \( \Delta v \), for the 101 rotators in our sample with six-parameter positions and kinematics by subtracting off the cluster median values for each \( UVW \) component and then adding the residuals in quadrature. The Hyades’s internal velocity dispersion is estimated to be only 0.3 km s\(^{-1}\) (Gunn et al. 1988; Perryman et al. 1998), which is comparable to the DR2 radial velocity (RV) error. We adopt a more conservative threshold for identifying nonsingle members of \( \Delta v > 2 \text{ km s}^{-1} \), which eliminates 26 stars. We also consider stars with DR2 RV errors \( \sigma_{\text{RV}} > 2 \text{ km s}^{-1} \) to be nonsingle members, which cuts an additional four stars, so that in the end we have 71 single-star rotators in our sample.

For Praesepe, we first remove the 43 binaries confirmed in the literature. Then, we filter nonsingle member stars using proper motions separately from RVs. This is possible because Praesepe is more distant than the Hyades and useful because 719 of 743 rotators have DR2 proper motions, whereas only 185 have DR2 RVs. The distribution of proper motions for our rotator sample can be approximately described by a Gaussian with \( \sigma = 1.25 \text{ mas yr}^{-1} \) (the median proper-motion error is 0.2 mas yr\(^{-1}\)). We set our threshold at twice this value and reject stars with absolute proper-motion deviations larger than this 2.5 mas yr\(^{-1}\). This eliminates 146 of 719 stars with DR2 proper motions. Separately, we reject 48 stars with \( \Delta \mu \chi > 2 \text{ km s}^{-1} \) from the cluster median value quoted by Gaia Collaboration et al. (2018a) and 46 stars with \( \sigma_{\mu \chi} > 2 \text{ km s}^{-1} \). In total, we reject 196 unique nonsingle members and retain 523 single-star rotators.

#### 6.1.2. Photometry

We use the Gaia Collaboration et al. (2018a) Hyades catalog to generate a fiducial cluster CMD and then iteratively fit the resulting main sequence with a cubic basis spline. We then generate a new CMD using our full rotator list and determine each star’s deviation from the fiducial main sequence.

We fit two CMDs: absolute \( G \) magnitude, \( M_G \), versus both \( (G_{\text{BP}} - G_{\text{RP}}) \) and \( (G - G_{\text{RP}}) \). We analyze \( (G - G_{\text{RP}}) \) to account for the larger uncertainty in \( G_{\text{BP}} \) for redder/fainter stars. We then calculate the photometric deviation from these empirical main sequences for our rotator sample, \( d_{\text{cmd}} = |M_G_{\text{observed}} - M_G_{\text{predicted}}| \), and label all stars that are consistent with at least one of the empirical isochrones as photometric single-member stars. We set a threshold of \( d_{\text{cmd}} < 0.375 \) mag for all stars, which is half of the offset for an equal-mass binary (e.g., Hodgkin et al. 1999). We find that 176 of 222 Hyads with DR2 photometry are consistent with being single-stars members.

For Praesepe, we adjust the fiducial Hyades CMD fit according to its interstellar reddening/extinction that we derive

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**Table 4**: Praesepe Stars with Measured \( P_{\text{rot}} \)

| 2MASS | EPIC | \( P_{\text{rot}} \) (days) | \( P^a \) | \( T_{\text{eff}} \) | DR2Nameb | Single Flag |
|-------|------|-----------------|------|-----------------|---------|-----------|
| ...   | ...  | 3.96            | 2    | 6196.83         | 66143826080277984 | NYYNN    |
| ...   | ...  | 14.59           | 2    | 4019.60         | 661211147230556032 | YYYY     |
| 08401747+2154567 | 212094548 | 6.60           | 2    | 3907.71         | 6651789191404024944 | YYYY-Y   |
| 08395507+2003542 | 211988287 | 3.29           | 2    | 6395.48         | 66342734376175040 | YYYY     |
| 08400063+1948235 | 211971871 | 2.99           | K    | 6289.11         | 66131175244248960 | YYYY     |
| 08400130+2008082 | 211992776 | 1.18           | 2    | 6597.70         | 663428915529294976 | YYYY     |
| 08402232+2006244 | 211900908 | 2.59           | K    | 6333.77         | 66141925967454976 | YYYY     |
| 08401763+1947152 | 211970750 | 6.69           | K    | 6054.54         | 661310709468509952 | YYYN     |

Notes.

8 For the Hyades, \( (U, V, W) = (+42.3, -19.2, -1.2) \text{ km s}^{-1} \).

9 For reference, a 0.5 km s\(^{-1}\) velocity dispersion at the distance of Praesepe (186 pc) translates to \( \approx 0.57 \text{ mas yr}^{-1} \).

10 For Praesepe, \( \mu_v \cos \delta, \mu_b = [-36.047, -12.917] \text{ mas yr}^{-1} \).
with DR2 photometry are consistent with being single-star members.

6.1.3. Astrometric Data Quality

The Gaia DR2 astrometric solution for each star assumes it is a single point source. Objects that are inconsistent with this assumption can have excess astrometric noise ($\epsilon_i$), and we remove those with $\epsilon_i > 1$ and $G < 19$ mag from our samples. This includes 40 stars in the Hyades and 48 stars in Praesepe. Most were already filtered by our kinematic and photometric selection criteria.

6.1.4. $P_{\text{rot}}$ Quality and Corrections

For rotators with K2 light curves, we remove those for which we detect multiple periods, which, again, we interpret as either physically unassociated blends or cluster binaries (see Sections 4 and 5.2).

For Praesepe, an additional step is required: several periods in the literature need to be corrected. In Douglas et al. (2017), we assembled literature periods and our own K2 periods and then recommended which source to use for each star. We recommended Delorme et al. (2011) for EPIC 211995288 and Scholz & Eislöffel (2007) for EPIC 211970147 (K2-102; Mann et al. 2017). But after reinspecting the K2 light curves, it is clear that our K2 periods are accurate and the literature values are half-period harmonics.

The Campaign 5 light curves for EPIC 211890774 and EPIC 211822797 (K2-103; Mann et al. 2017) both show weak asymmetries in the depths of alternating minima, which we confirm with their Campaign 16 light curves. This indicates that the Douglas et al. (2017) measurements for these two stars are half-period harmonics, caused, presumably, by nearly symmetric spot patterns on opposite-facing hemispheres. We therefore double the old $P_{\text{rot}}$ for these stars.

Finally, EPIC 211950227 was originally given a period of 13.15 days (Delorme et al. 2011). However, the Campaign 16 light curve shows that the dominant modulation signal has a period of $P_{\text{rot}} = 1.76$ days. We see no $\approx 13$ day signature in its Campaign 16 light curve and conclude that the K2-derived $P_{\text{rot}}$ is the correct one.

6.2. Resulting CMDs and $T_{\text{eff}}$–$P_{\text{rot}}$ Distributions for the Hyades and Praesepe

The resulting CMDs for the two clusters are shown in the left column of Figure 7, with their $T_{\text{eff}}$–$P_{\text{rot}}$ distributions in the right column. Applying the cuts described above yields a nearly clean $P_{\text{rot}}$ distribution for both clusters. Overall, 118 Hyades rotators out of 232 satisfy our single-star-membership criteria. When examining the cluster’s $P_{\text{rot}}$ distribution, we find no rapid outliers relative to the cleaned, slow-rotating sequence for $M_\ast \gtrsim 0.57 M_\odot$ ($T_{\text{eff}} \gtrsim 3789$ K) and only three moderately faster rotators for $M_\ast \gtrsim 0.5 M_\odot$ ($T_{\text{eff}} \gtrsim 3620$ K). The transition to completely rapid rotation in the Hyades occurs at $M_\ast \approx 0.35 M_\odot$ ($T_{\text{eff}} \approx 3420$ K, M3), which is slightly warmer than the $T_{\text{eff}}$–radius discontinuity at $T_{\text{eff}} = 3200$–3340 K identified by Rabus et al. (2019).

For Praesepe, we find that 496 of the 743 rotators are consistent with being single-star members. None of these stars appears significantly more rapid than the converged slow sequence for $T_{\text{eff}} \gtrsim 3845$ K ($M_\ast \gtrsim 0.6 M_\odot$, M0). Of the 43 single members on our list with $3600 < T_{\text{eff}} < 3850$ K, 10, or 23%, are rapidly rotating outliers that have $P_{\text{rot}}$ faster than the slow sequence by at least 3 days. The transition to all rapid rotators happens around $M_\ast \approx 0.4 M_\odot$ ($T_{\text{eff}} \approx 3500$ K) but is not as well defined as in the Hyades.

Finally, Pr0211 (EPIC 211936827, Gaia DR2 66122279785743616) hosts a hot Jupiter ($M_\text{p} \sin i = 1.844 M_\text{Jup}$, $P_{\text{orb}} = 2.15$ days; Quinn et al. 2012). We find that Pr0211 rotates 1.4 days (15%) faster than expected, in agreement with Kovács et al. (2014).

6.3. A Precise Differential Gyrochronology Age for the Hyades

We now turn to the question of whether Praesepe and the Hyades are truly coeval. We search the literature and tabulate recent isochrone ages for the two clusters derived using a variety of photometry, constraints, models, and methods (see Table 1). From these, we calculate an age for the Hyades of 728 ± 71 Myr (median and 1σ of 13 values) and for Praesepe of 670 ± 67 Myr (median and 1σ of 11 values). Since this suggests that Praesepe is the younger of the two clusters, we then calibrate an empirical gyrochronology model by fitting the Praesepe $T_{\text{eff}}$–$P_{\text{rot}}$ sequence and then tune the age dependence with the Sun. Finally, we compare the $T_{\text{eff}}$–$P_{\text{rot}}$ sequences of the Hyades and Praesepe and derive a precise differential age according to our empirical model.

We summarize our assumed values for the Sun here. We take the Sun’s $P_{\text{rot}} = 26.09$ days, measured from periodic modulations in the Mount Wilson CaII H & K index by Donahue et al. (1996). We take its age to be $4567 \pm 1 \pm 5$ Myr (Chaussidon 2007). Based on observations of solar twins derived from the updated Spectroscopic Properties of Cool Stars (SPOCS; Brewer et al. 2016) catalog, we derive a solar color of $(G_{BP} - G_{RP})_\odot = 0.817$ mag, consistent with the value of $(G_{BP} - G_{RP})_\ast = 0.82$ estimated by Casagrande & VandenBerg (2018). A more detailed discussion of our derivation of this color can be found in Appendix B.

Our analysis also makes the following assumptions.

1. The Sun has slowed down continuously since it was 670 Myr old (our adopted age of Praesepe). According to van Saders et al. (2016), magnetic braking efficiency plummets at a critical Rossby number (the ratio of $P_{\text{rot}}$ to convective turnover time) of $R_{\text{rot}} = 2$, approximately the current solar value. We assume that the Sun has not yet reached this threshold and that it has therefore spun down continuously with a single-valued time dependence.

2. The difference in metallicity between the Sun and Praesepe does not appreciably affect spin-down, and comparing equal-color stars is valid, even though a solar-mass star in Praesepe is cooler than the Sun’s current temperature.11

11 Stars do not spin down through $T_{\text{eff}}$–$P_{\text{rot}}$ space along perfectly vertical lines, since they warm as they age. Differences in metallicity will also modify moments of inertia, convective turnover times, and other physical ingredients that are critical to understanding angular momentum evolution. Theoretical models are the appropriate way of accounting for metallicity and stellar-evolution effects (e.g., van Saders & Pinsonneault 2013), but we presently lack sufficient coeval benchmarks with different metallicities to validate their predictions. Also, all available models fail to represent the cluster sample, aside from the most Sun-like G dwarfs (e.g., Agüeros et al. 2018, Curtis et al. 2019, and this work). Since our primary goals are to test if the Hyades and Praesepe are truly coeval and to measure a differential age, any systematic inaccuracies in the model will propagate to both cluster ages equally.
We fit a sixth-order polynomial to Praesepe’s cleaned and dereddened DR2 color–period sequence for stars with \((G_{BP} - G_{RP}) < 2.4\) \((T_{\text{eff}} \approx 3500\, \text{K}, M \approx 0.42\, M_\odot, 2\, \text{M}_\odot)\). This color limit stops our model before the sharp drop to rapid rotation around the fully convective boundary. The sixth-order polynomial is necessary, as lower-order polynomials fail to accurately track the rapid change in \(P_{\text{rot}}\) from F to G dwarfs. The final polynomial we use is

\[
P_{\text{rot}} = -330.81005 + 1462.4834(G_{BP} - G_{RP}) - 2569.3548(G_{BP} - G_{RP})^2 + 2347.1325(G_{BP} - G_{RP})^3 - 1171.8965(G_{BP} - G_{RP})^4 + 303.61984(G_{BP} - G_{RP})^5 - 31.922667(G_{BP} - G_{RP})^6.
\] (1)

The Praesepe fit predicts a period at the solar color of \(P_{\text{rot}} = 8.09 \pm 0.25\, \text{days}\). We calculate this value using a \(T_{\text{eff}} - P_{\text{rot}}\) diagram dereddened by our \(A_V = 0.035\) value, while the uncertainty comes from assuming either \(A_V = 0\) (no reddening) or \(A_V = 0.084\) (Taylor 2006). We use the age for Praesepe derived from the literature of 670 Myr and calculate that the braking index \(n = 0.619\).

We now apply our new gyrochronology formula to the cleaned stars in the Hyades with \(0.7 < (G_{BP} - G_{RP}) < 1.1\), where gyrochronology should be viable at this age (Agüeros et al. 2018; Curtis et al. 2019). If Praesepe is 670 Myr old and its \(A_V = 0.035\), and if it is chemically identical to the Hyades, then the Hyades is 57 Myr older. We find the Hyades age to be \(727 \pm 75\, \text{Myr}\) (median and 1\(\sigma\)) based on 25 cluster members. (For 49 analogous Praesepe stars, 1\(\sigma\) = 69 Myr.) Recall that we calculate an isochrone age difference of 58 Myr by computing the difference between the median of various isochronal ages for each cluster; this is essentially identical to our differential gyrochronology result.

Figure 8 shows the \(T_{\text{eff}} - P_{\text{rot}}\) diagram for the cleaned Praesepe and Hyades samples and their corresponding gyrochronology ages using our recalibrated formula. Derived ages for individual stars are given in Table 5.

### 7. Discussion

New \(P_{\text{rot}}\) measurements from \(K2\) and precise \(Gaia\) data have enabled us to compare the rotation distributions in Praesepe and the Hyades in detail. Whereas in previous work, we assumed that the clusters have overlapping \(P_{\text{rot}}\) sequences, we now find that is not the case for solar-type stars. Overall, we find that Hyades FG stars rotate more slowly than their Praesepe counterparts, corresponding to a differential gyrochronological age of 57 Myr. This difference is consistent with the 47 ± 17 Myr difference between the clusters found by Delorme et al. (2011), who used a linear fit to the \(P_{\text{rot}}\) versus \((J - K_s)\) relation in the Hyades and Praesepe. The 57 Myr age difference suggests that the two clusters should be separated when considering the evolution or effects of stellar rotation in solar-type stars and when accuracy below the 10% level is required.

Interestingly, the age discrepancy between the two clusters is largest for \(T_{\text{eff}} > 5200\, \text{K}\) and decreases as we move to cooler stars. We fit the gyrochronology ages of Hyades stars with locally weighted scatter-plot smoothing (LOWESS) as a function of \(T_{\text{eff}}\) and compare it to the fiducial Praesepe model (Figure 9). In the range \(5250\, \text{K} > T_{\text{eff}} > 4900\, \text{K}\), the differential gyro ages decrease, so that cooler Hyads converge with the Praesepe sequence. The late K and early M dwarfs do not break appreciably from the age of Praesepe to that of the Hyades. This contradicts the common assumption that braking timescales increase as mass decreases. Our work therefore adds to prior evidence that low-mass stars follow a different, more complex braking timeline than their solar-type counterparts.

Several other authors have reached similar conclusions. Meibom et al. compared M35 \((\approx 150\, \text{Myr}; \text{Meibom et al. 2009})\), M34 \((\approx 220\, \text{Myr}; \text{Meibom et al. 2011b})\), and NGC 6811 \((\approx 1\, \text{Gyr}; \text{Meibom et al. 2011a})\) to the Hyades and found that K dwarfs must spin down less efficiently than FG stars. Cargile et al. (2014) found the same result by comparing Blanco 1 and the Pleiades (both \(\approx 125\, \text{Myr}\)) to M37 \((\approx 550\, \text{Myr})\), the Hyades, and NGC 6811. Similarly, Agüeros et al. (2018) found evidence for stalling from the age of Praesepe to that of NGC 752 \((\approx 1.3\, \text{Gyr})\) for K and early M stars. Finally, Curtis et al. (2019) reexamined NGC 6811 by searching \(Gaia\) DR2 for additional members with \(Kepler\) light curves, thereby significantly expanding the size of that cluster’s rotator sample and extending it down in mass from \(M \approx 0.8\) to \(\approx 0.6\, M_\odot\).

Surprisingly, these authors found that NGC 6811’s slow-rotator sequence converges with that of the Hyades and Praesepe at redder colors, indicating that these stars effectively do not spin down at all over a time span of several hundred Myr.

We therefore provide concrete evidence that K stars spin down at a variable rate, as opposed to existing empirical models, which show them spinning down continuously from the time they reach the main sequence. This stalling is apparent even over \(\approx 50\, \text{Myr}\) timescales. Previous empirical work has assumed a fixed functional form for the dependence of \(P_{\text{rot}}\) on mass or \((B - V)\) at all ages. For example, Delorme et al. (2011) fit a line to the \(P_{\text{rot}}\) versus \((J - K_s)\) distributions in clusters, and Barnes (2003, 2007) fit other analytic functions. These efforts assumed that it was possible to decouple the mass and age dependencies, but our results demonstrate that rotation evolves at different rates for stars of different masses.

Barnes (2010) presented the only empirical gyrochronology relation that allowed more complicated mass-dependent evolution by including a dependence on the convective turnover time \(\tau\) instead of color. That model accurately described the \(M \geq 0.85\, M_\odot\) stars in the 2.5 Gyr NGC 6819 cluster (Meibom et al. 2015). However, it actually predicted that K dwarfs spin down more rapidly than G dwarfs, instead of more gradually, as indicated by the open cluster data. Mamajek \\

\& Hillenbrand (2008), Meibom et al. (2009), and, more recently, Angus et al. (2015) simply recalibrated the model presented by Barnes (2003, 2007) without considering more complex mass-dependent rotational evolution.

One probable reason that empirical models have not included a mass dependence is the paucity of \(\geq 1\, \text{Gyr}\) old benchmarks for K and M dwarf rotators. The \(P_{\text{rot}}\) have been published for solar-type members of NGC 6819 and M67, but not their lower-mass members. We show that this dependence is present even over short timescales, but the field of gyrochronology requires additional benchmarks at older ages to properly calibrate braking timescales for stars of different masses. Future
work on NGC 6819 and Ruprecht 147, also \( \approx 2.5 \) Gyr old, will provide further constraints on mass-dependent evolution at older ages.

For the time being, when examining effects at a single age, we can consider the low-mass rotators in the Hyades and Praesepe as a single ensemble. The low-mass rotators deserve additional consideration in future work, but this will first require comprehensive binary surveys of late K and early M dwarfs to disentangle evolutionary effects from multiplicity effects in these clusters. Several authors have found tentative evidence that binaries rotate faster than single stars (e.g., Meibom et al. 2007; Douglas et al. 2016, 2017), which is one reason why we remove known binaries from our sample above.

The Hyades and Praesepe, however, have not been uniformly surveyed for binaries, particularly at the low-mass end. In our \( K2 \) analysis, we identify candidate binaries via blends and multiple periods detected in a single light curve. However, these candidates could be chance alignments or (when the two periods are very similar) a signal of latitudinal differential rotation.

NASA’s ongoing Transiting Exoplanet Survey Satellite mission (TESS; Ricker et al. 2015) will also provide an excellent opportunity for expanding the \( P_{\text{rot}} \) catalog for Hyades M dwarfs. Many Hyades M dwarfs lie on the outskirts of the cluster (with many more potentially found in unbound tidal tails; Röser et al. 2019), far enough from the ecliptic to be
observed by TESS. Although there will certainly be issues with systematics, given the standard 27.4 day observing cadence, we expect to measure $P_{\text{rot}}$ for $\approx 200$ Hyads in the southern hemisphere alone (TESS Program G011197). Many more Hyads, as well as members of another approximately coeval Coma Ber cluster (Collier Cameron et al. 2009), will be observed by TESS in the northern hemisphere. Since one current challenge in comparing the Hyades and Praesepe is the much smaller Hyades $P_{\text{rot}}$ catalog, future TESS measurements will be invaluable for differentiating the behavior of M dwarfs in these similarly aged clusters.

8. Conclusions

We analyze K2 Campaign 13 light curves for 323 members of the Hyades open cluster. We measure $P_{\text{rot}}$ for 116 (88%) of these stars, including 93 members with no prior $P_{\text{rot}}$ measurements, bringing the total number of Hyads with known $P_{\text{rot}}$ to 232. As in our last two papers (Douglas et al. 2016, 2017), we find that ground-based $P_{\text{rot}}$ measurements are generally consistent with space-based measurements. The primary difference is that space-based observatories can observe a wide field of view nearly continuously while simultaneously reaching even faint members of nearby open clusters.

We then use Gaia DR2 data and literature binary information to define a clean sequence of single-star Hyads in color–magnitude space. We then apply this procedure to data for the Praesepe open cluster, which is generally thought to be coeval with the Hyades. As a result, we obtain two clean sequences of slowly rotating FGK stars in $T_{\text{eff}}$–$P_{\text{rot}}$ space for both clusters. There are far fewer known binaries among the M dwarfs in these two clusters. But our cuts also produce a nearly clean slow-rotator sequence for early M dwarfs, with only a few rapidly rotating members in this mass range in both clusters. These remaining rapid rotators highlight the need for additional binary surveys of M dwarfs in these clusters, especially Praesepe.

We use these single-star sequences to derive a reddening value of $A_V = 0.035 \pm 0.011$ mag for Praesepe, assuming that...
the Hyades experiences no reddening. This value is inter-
mediate between the oft-assumed $A_V = 0.0$ and the
$A_V = 0.084$ mag derived by Taylor (2006) for Praesepe. We
then derive a polynomial fit to the slow-rotator sequence in
Praesepe as a function of dereddened Gaia DR2 ($G_{BP} - G_{RP}$)
color. We use this fit as the basis for a new empirical model for
gyrochronology, where we assume that stars begin on the
Praesepe sequence at 670 Myr and their periods evolve as $P_{\text{rot}} \propto t^n$. By comparing the Praesepe sequence to the Sun, we
derive a value of $n = 0.619$.

Finally, we compare the slow-rotator sequence in the Hyades
to this model we have generated based on Praesepe. We find
that, if we only consider the F and G stars, the Hyades is
57 Myr older than Praesepe. We also find, however, that the
difference between the Hyades and Praesepe sequences
decreases toward lower-mass stars, so that the K and early M
dwarfs in the two clusters are indistinguishable. This provides
further evidence for stalling in the rotational evolution of these
stars and highlights the need for more detailed analysis of spin-
down over time for stars of different masses.

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graphic data obtained using the Oschin Schmidt Telescope on
Palomar Mountain and the UK Schmidt Telescope. The plates
were processed into the present compressed digital form with
the permission of these institutions.

**Facility:** Kepler (K2).

**Software:** Astropy (Astropy Collaboration et al. 2013),
Astroquery (Ginsburg et al. 2019), AstroML (VanderPlas
et al. 2012; Ivezić et al. 2013), pywcsgrid2 (J. Lee),12 K2fov
(Mullally et al. 2016).

**Appendix A**

**Nonzero Reddening in Praesepe**

Praesepe suffers little interstellar reddening and extinction.
Many studies—including our own prior work—assume zero
reddening (e.g., Douglas et al. 2014; Angus et al. 2015;
Cummings et al. 2017; Douglas et al. 2017) due to the cluster’s
close proximity to Earth. Taylor (2006), however, found
$E(B-V) = 0.027$ (or $A_V = 0.084$).

Interstellar reddening is often constrained with color–color
diagram or CMD analyses. We take an alternative approach
using spectroscopy. Coauthor J. Brewer observed members of
the Hyades and Praesepe with Keck/HIRES for a separate
project and analyzed the spectra with Spectroscopy Made Easy
(Valenti & Fischer 2005) following the Brewer et al. (2015)
procedure (see also Brewer et al. 2016; Brewer & Fischer 2018).
We match their target list with Gaia DR2 and filter out nonsingle
star members according to their proximity to the empirical
cluster main sequence defined by the Gaia Collaboration et al.
(2018a) membership list and their astrometry. We also only
focus on those stars with $5000 \text{ K} < T_{\text{eff}} < 6200 \text{ K}$, giving us 20
FGK stars in our Hyades sample and nine in our Praesepe
sample.

We fit an empirical color–temperature relation to the Hyades
sample and define its reddening to be zero. Figure 10 compares
the Praesepe stars with their Hyades analogs and shows that the
Praesepe stars have photometric temperatures that are system-
atically cooler than their spectroscopic temperatures. Spec-
troscopic and photometric temperatures for individual stars are
given in Table 6. We then calculate the necessary reddening
values for each star in the Hyades and Praesepe needed to align
their photometric and spectroscopic temperatures. We find
$A_V = 0.035 \pm 0.011$ (median and 1$\sigma$) for Praesepe. Our result
splits the difference between the Taylor (2006) value and the

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12 https://github.com/leejoon/pywcsgrid2
Table 6

Praesepe and Hyades Members Used to Derive the Differential Reddening between the Two Clusters

| Cluster | DRName | SpecTeff | (G_{BP} - G_{RP}) | PhotTeff |
|---------|--------|----------|-------------------|----------|
| Praesepe | 662925629454594944 | 5988 | 0.785 | 5939.1342 |
| Praesepe | 6646831300790043136 | 5811 | 0.841 | 5758.5828 |
| Praesepe | 66284137375655933 | 5420 | 0.959 | 5398.3781 |
| Praesepe | 659539236719284768 | 6028 | 0.768 | 5993.4307 |
| Praesepe | 659766114072502608 | 5083 | 1.111 | 5049.5066 |
| Praesepe | 659343626729512832 | 6034 | 0.771 | 5981.6420 |
| Praesepe | 66460084138934400 | 5390 | 0.969 | 5371.2551 |
| Praesepe | 664366779961036288 | 5510 | 0.930 | 5484.3133 |
| Praesepe | 65976803821739568 | 5747 | 0.858 | 5704.8021 |
| Hyades | 47019347749289216 | 5141 | 1.055 | 5157.4270 |
| Hyades | 52548214968465408 | 5345 | 0.979 | 5344.6499 |
| Hyades | 49005581144118874 | 5527 | 0.907 | 5522.1841 |
| Hyades | 47345009348203392 | 5622 | 0.886 | 5617.7784 |
| Hyades | 3312644885984344704 | 5540 | 0.912 | 5535.8121 |
| Hyades | 3312575685471393664 | 5938 | 0.793 | 5912.2090 |
| Hyades | 3309956805635519488 | 5216 | 1.035 | 5200.8830 |
| Hyades | 3309000602007842048 | 5787 | 0.831 | 5789.9270 |
| Hyades | 3411887595780736128 | 5252 | 1.026 | 5223.1113 |
| Hyades | 3406823245223942528 | 5273 | 1.004 | 5277.6612 |
| Hyades | 3405113740864365440 | 6065 | 0.738 | 6088.7928 |
| Hyades | 3407128133907301128 | 5583 | 0.894 | 5590.8317 |
| Hyades | 100254161710940928 | 5787 | 0.838 | 5769.1275 |
| Hyades | 84790943716056532 | 5051 | 1.190 | 5056.6869 |
| Hyades | 10608573516849536 | 5959 | 0.775 | 5970.9793 |
| Hyades | 14900520733720192 | 5831 | 0.821 | 5821.3471 |
| Hyades | 14532554816513280 | 5498 | 0.919 | 5516.2169 |
| Hyades | 3313689422030650496 | 5805 | 0.830 | 5795.3730 |
| Hyades | 3306922958753764992 | 6141 | 0.725 | 6128.2910 |
| Hyades | 3309170875916905856 | 5829 | 0.816 | 5840.2860 |

Figure 10. Difference between photometric (T_{phot}) and spectroscopic (T_{spec}) effective temperatures for 20 FGK members of the Hyades (orange diamonds) and nine of Praesepe (blue circles) are plotted against T_{spec}. The T_{phot} values are estimated based on the relationship between the Gaia DR2 color (G_{BP} - G_{RP}) and T_{spec} for the Hyades, which we assume appear to us unreddened. We interpret stars with T_{phot} < T_{spec} as reddened and extinguished by interstellar dust. Based on Praesepe’s median negative offset, we estimate A_V = 0.035 ± 0.01 for that cluster.

Appendix B

The Sun’s Gaia DR2 Color

Since Gaia cannot observe the Sun’s disk-integrated light, we must instead estimate its Gaia color with analogous field stars. We select stars in the updated SPOCS catalog (Brewer et al. 2016) with spectroscopic properties most similar to the Sun’s, identifying 11 stars with T_{eff} within 100 K of 5777 K (the solar T_{eff} adopted by SPOCS), log g > 4.3 dex, [Fe/H] within 0.05 dex of solar, and log R'_{HK} < −4.8 dex.

We then fit a cubic polynomial relating T_{eff} to color for these stars, finding that T_{eff} = 5777 K predicts a solar color (⟨G_{BP} - G_{RP})⟩_☉ = 0.817 mag. This empirical value is in excellent agreement with that of Casagrande & VandenBerg (2018), who estimated the solar color from a variety of spectral templates to be (⟨G_{BP} - G_{RP})⟩_☉ = 0.82 mag.

The SPOCS star that we decided was most similar to the Sun is HD 103828 (Gaia DR2 84547146339146496). It has the following spectroscopic properties in Brewer et al. (2016): T_{eff} = 5771 K, log g = 4.39 dex, metallicity [M/H] = −0.02 dex, and v sin i = 1.2 km s^{-1}. The average chromospheric emission is log R'_{HK} = −4.846 (Isaacson & Fischer 2010), corresponding to a chromospheric age of 3.89 Gyr (Mamajek & Hillenbrand 2008). The [Y/Mg] abundance ratio implies an age of 6.4 Gyr (Spina et al. 2018). The DR2 color for this star is (⟨G_{BP} - G_{RP})⟩_☉ = 0.8162 mag.

Also quite similar to the Sun, HD 222582 (Gaia DR2 2440578577126302336) has T_{eff} = 5789 K, log g = 4.38 dex, [M/H] = +0.01 dex, and v sin i = 0.5 km s^{-1}. The average chromospheric emission is log R'_{HK} = −4.922 (Isaacson & Fischer 2010), corresponding to a chromospheric age of 5.2 Gyr (Mamajek & Hillenbrand 2008). The [Y/Mg] abundance ratio implies an age of 6.7 Gyr (Spina et al. 2018). The DR2 color for this star is (⟨G_{BP} - G_{RP})⟩_☉ = 0.8201 mag.

The solar twin 18 Sco (HD 146233) has T_{eff} = 5785 K, log g = 4.41 dex, [M/H] = +0.04 dex, v sin i = 1.5 km s^{-1}, and log R'_{HK} = −4.933 dex. It has a DR2 color of 0.8081 mag, which is only 0.009 less than our adopted solar value.
