ROTATION PERIODS FOR COOL STARS IN THE 4 Gyr OLD OPEN CLUSTER M67, THE SOLAR– STELLAR CONNECTION, AND THE APPLICABILITY OF GYROCHRONOLOGY TO AT LEAST SOLAR AGE

Sydney A. Barnes\textsuperscript{1,3}, Jörg Weingrill\textsuperscript{1}, Dario Fritzewski\textsuperscript{1}, Klaus G. Strassmeier\textsuperscript{1}, and Imants Platais\textsuperscript{2}

\textsuperscript{1}Leibniz Institute for Astrophysics (AIP), Potsdam, Germany; sbarnes@aip.de
\textsuperscript{2}Department of Astronomy, Johns Hopkins University, Baltimore, MD, USA

Received 2015 December 23; accepted 2016 March 25; published 2016 May 16

ABSTRACT

We report rotation periods for 20 cool (FGK) main sequence member stars of the 4 Gyr-old open cluster M67 (=NGC 2682), obtained by analyzing data from Campaign 5 of the \textit{Kepler Space Telescope}. The rotation periods delineate a sequence in the color–period diagram (CPD) of increasing period with redder color. This sequence represents a cross-section at the cluster age of the surface $P = \mathcal{P}(t, M)$, suggested in prior work to extend to at least solar age. The current Sun is located marginally (approximately $1\sigma$) above M67 in the CPD, as its relative age leads us to expect, and lies on the $P = \mathcal{P}(t, M)$ surface to within measurement precision. We therefore conclude that the solar rotation rate is normal as compared with cluster stars, a fact that strengthens the solar–stellar connection. The agreement between the M67 rotation period measurements and prior predictions further implies that rotation periods, especially when coupled with appropriate supporting work such as spectroscopy, can provide reliable ages via gyrochronology for other similar FGK dwarfs from the early main sequence to solar age and likely until the main sequence turnoff. The M67 rotators have a rotational age of 4.2 Gyr with a standard deviation of 0.7 Gyr, implying that similar field stars can be age-dated to precisions of $\sim 17\%$. The rotational age of the M67 cluster as a whole is therefore 4.2 Gyr, but with a lower (averaged) uncertainty of 0.2 Gyr.

Key words: open clusters and associations: individual (M67, NGC 2682) – stars: activity – stars: evolution – stars: rotation – stars: solar-type – starspots

1. INTRODUCTION

Our Sun is the archetype for a vast plurality of stars, particularly main sequence cool stars, i.e., those with surface convection zones (Schatzman 1962).\textsuperscript{4} This idea is enshrined in a Copernican principle whose origins go back to ancient Greece, and in research circles today is called "the solar–stellar connection" (e.g., Mihalas 1981; Sofia & Endal 1987; Strassmeier 2004; Brun et al. 2015).

Various pillars of this solar–stellar connection include the consonance between the Sun on the one hand and similar stars in the Galaxy on the other hand in terms of, e.g., chromospheric activity levels (Eberhard & Schwarzschild 1913; see Hale & Ellerman 1904; Wilson 1963), the lengths of their magnetic cycles (Wilson 1978; Baliunas et al. 1995), photometric variability (Lockwood et al. 2007, 2013), and characteristics of their starspots (Kron 1947; Vogt & Penrod 1983; Strassmeier 2009).

The chromospheric activity of solar-type stars in particular has been carefully studied over the years and is known from open cluster work to decline systematically enough with stellar age to be used as a reliable, if coarse, age indicator (e.g., Wilson 1963; Skumanich 1972; Noyes et al. 1984; Soderblom et al. 1991; Donahue 1998; Mamajek & Hillenbrand 2008). However, the large distances to old clusters coupled with meager chromospheric emission from old stars mean that we are forced to work with nearby field stars such as the Mount Wilson sample (e.g., Baliunas et al. 1996), whose ages are not independently known.\textsuperscript{5} This has made it difficult to assess the activity of solar-age stars. To clarify this part of the solar–stellar connection, Giampapa et al. (2006) studied chromospheric activity in solar-type stars of M67 and found both a mean activity level resembling solar values and a wide activity range, the latter suggesting caution, perhaps even pessimism, in using this activity routinely as an age indicator.

The solar–stellar connection is also invoked in models of stellar spin-down (e.g., Endal & Sofia 1981; Kawaler 1988; Pinsonneault et al. 1989) because these both reasonably assume that the angular momentum loss from the magnetized solar wind (Parker 1958; Weber & Davis 1967) is a good model for other cool star winds, and they also calibrate the efficiency of angular momentum loss by requiring that a solar-mass stellar model has the solar rotation period (26.09 d at the average sunspot latitude; Donahue et al. 1996) at the solar age.

In terms of rotation itself, data acquired steadily over the last 50 years initially showed that the rotation velocities—and since the 1980s, that the less ambiguous rotation periods, $P$, of late-type main sequence stars—are largely dependent on stellar age, $t$, and mass, $M$, or other suitable mass proxies such as $(B−V)_0$ color (Kraft 1967; Skumanich 1972; van Leeuwen & Alphenaa 1982; Radick et al. 1987; Kawaler 1989; Barnes 2003, 2007; Meibom et al. 2011, 2015). This relationship can be represented by a surface $P = \mathcal{P}(t, M)$ in the corresponding three-dimensional $(P, t, M)$ space, which can then be inverted analytically or numerically to provide the star’s age $t = \mathcal{P}(P, M)$, a procedure known as gyrochronology (Barnes 2003, 2007, 2010).

A key observational goal has been to define the $P = \mathcal{P}(t, M)$ surface empirically to the oldest-possible ages by measuring rotation periods for cool cluster member stars in a succession of open clusters, each cluster sampling a slice of this surface at
constant age. Clusters, after all, provide homogeneous and coeval stellar samples whose ages—isochrone or otherwise—are hugely more reliable than those of field stars (e.g., Sandage 1962; Demarque & Larson 1964). Kepler observations of key open clusters, coupled with onerous but essential membership and multiplicity surveys, have already extended the known surface beyond the 625 Myr age of the Hyades (Radick et al. 1987; Delorme et al. 2011), first to 1 Gyr (NGC 6811; Meibom et al. 2011) and recently to 2.5 Gyr (NGC 6819; Meibom et al. 2015).

The Sun apparently lies on the same surface as that defined by the open clusters, but because the oldest available cluster to date (NGC 6819) is still ~2 Gyr younger than the Sun, there is room for ambiguity. K2 observations of the open cluster M67, believed to be ~4 Gyr old (Demarque et al. 1992; VandenBerg & Stetson 2004; Bellini et al. 2010), make it possible to extend the $P = \rho(t, M)$ surface out to near-solar age and to assess to what extent the Sun does (or does not) lie on it. If it does, then the $(P, t, M)$ relationship is likely valid for the entire main sequence until the turnoff, as the rotation periods of the Mount Wilson field star sample seem to suggest (see e.g., Baliunas et al. 1996; Barnes 2003, 2007). This issue is at the heart of the solar–stellar connection. It is addressed here by providing rotation periods for 20 cool (FGK) stars in M67.

2. DATA ANALYSIS

We downloaded the K2 (Campaign 5) timeseries data for all available main sequence targets from the MAST archive.\(^{8}\) We ignored the crowded (~1/4° square) central region of the cluster that is covered by a K2 superstamp and concentrated on the light curves for those individual K2 targets that are located in the annular region beyond this limit but within 1/2° from the center, and those that are listed in the recent M67 membership study of Geller et al. (2015; hereafter GLM15). Figure 1 displays the spatial locations of all GLM15 member stars (with a radial velocity membership probability greater than 50%) in the M67 region of the sky. We began with all released K2 stars listed in GLM15, regardless of their membership status to enable us to remove spacecraft, instrumental, and non-astrophysical signatures from the K2 light curves.

Although the presearch data conditioning (PDC) light curves provided by the K2 C5 data release have removed many of the spacecraft glitches, a global study of all available light curves clearly shows residual instrumental and/or spacecraft signatures which also need to be removed.\(^{7}\) We performed principal component analysis (PCA) with all light curves matched against epochs as specified by the K2 flag \texttt{CADENCE\_NO.}. PCA immediately shows that there are two major families of light curves that originate in the M67 stars located on two separate CCDs ("channels" in K2 jargon). These two groups follow each other relatively closely at the ~5 mmag level, but have differing characteristics below this level and were therefore corrected separately. Spacecraft drift is also visible in the PCA. There is also a small number of "light curves" with almost no signal. These were ignored in subsequent analysis.

We subtracted the mean flux for each light curve as well as the median for each epoch representing the central tendency of the entire ensemble of light curves. (This is equivalent to putting all stars on the same photometric system, normalizing each star’s flux to its mean value and removing the common trends.) This procedure decreased the rms for the individual channels by a factor of ~5, with the best-exposed light curves for the inactive stars at this stage giving an rms of 0.3 mmag over the whole light curve. (The presence of such “constant stars” informs us that data corrections are successful to this level and that variability above this level for comparably bright stars is likely intrinsic.) We also removed all data points with K2 flag \texttt{SAP\_QUALITY} that are greater than zero and followed it by linearly interpolating single missing data points (Weingrill 2015) to produce equidistant time steps, enabling the application of a low-pass one half-day filter, and the application of the regular fast Fourier transform (FFT). This procedure does not affect the power spectrum, as explained in Weingrill (2015), which describes the overall software framework for our studies and which originates in software developed to reduce CoRoT satellite data. Many light curves and power spectra show features from the “Argabrightening” event 38 d into C5. There are also residual effects from a coronal mass ejection at 55.5 d from C5 start. Data from the first and last days of K2 C5 observations were also found to be unstable enough that they had to be discarded. The final data set nominally consists of a 73 d timeseries.

Several high-amplitude variables (binaries etc.) are recognizable directly from the PCA analysis that is performed on all downloaded stars. However, these are not relevant to our aims, being either non-members or too bright so they were ignored. The period search algorithms were restricted to the 106 single and binary cluster members in the region of the color–magnitude diagram (CMD) below the turnoff at $V = 13.5$. Pulsators are not found in our region of the CMD (late-F to mid-K) and in any case would be easily identifiable from their power spectra. The light curves of a significant fraction (~30%) of the cool single and binary cluster members display distinctive mmag-level light curve modulations that are (and have long been) recognizable from ground-based and space

---

\(^{8}\) https://archive.stsci.edu/k2/

\(^{7}\) The data release notes are available at http://keplerscience.arc.nasa.gov. See also Van Cleve et al. (2015).
observations as originating in star spots. We observe activity and also significant evolution of the spots over the 75 d baseline of K2 observations.

Rotation periods were derived for these spotted variables using four principal methods: phase dispersion minimization (PDM; Stellingwerf 1978), minimum string length (SL; Dworetsky 1983), Bayesian period signal detection (GL; Gregory & Loredo 1999), and autocorrelation (AC; Scargle 1989). None of these methods make prior assumptions about the shape of the light curve, a fact which will be important in the sequel. We also used the FFT. However, because most of the light curves are not sinusoidal, (70% have two major spot groups; see Table 1) the FFT sometimes preferentially locks onto roughly half of the true period and was downplayed in this particular context. The domain for the period searches was set to 0.6 d < P < 37 d, with the long-period limit specified by our requirement that at least two phases be seen for each variable in the 75 d K2 observing window. Our period resolution is nominally 0.05 d. We generally sought period agreement between all four of the PDM, SL, GL, and AC methods to retain a given star, but all methods are not universally successful. The baseline of the K2 observations is long enough for significant spot evolution to be observed in most of the stars, and yet not long enough to provide multiple phases for these long-period stars. The final decision was made manually, guided by the noise properties of the individual light curves. We demanded that all accepted light curves have a dip in the PDM Θ statistic below Θ = 0.55, that this periodicity be obtained from at least two of the other methods, and that the light curves should demonstrate this variability subjectively upon visual examination.

As a result of the above procedure, we settled on 19 single and one binary cluster member stars displaying periodic spot-induced variability, and these will be our sole concern below.9 The locations of these 20 stars on the sky are marked in Figure 1 together with those of the other member stars in GLM15 with radial velocity membership probability $P_{RV} \geq 50\%$. The annular distribution of the sample as mentioned earlier is clearly visible.

The light curves for all stars are displayed in the accompanying Appendix together with the associated smoothed “power spectra” for the four principal period search methods used. The variability levels for the solar-type stars reported here are similar to that of the active Sun, and other stars in our sample have variability similar to that of the quiet Sun (Lockwood et al. 2007). The final chosen period and its error, calculated from Gaussian fits to the smoothed PDM spectra, are displayed in each power spectrum panel. Seventy percent (14/20) of the light curves show the presence of two large spot groups. The rotation periods themselves together with their uncertainties and other stellar information relevant to this paper are listed in Table 1.

Cluster membership probabilities are drawn from GLM15, providing both the line of sight (LOS) membership probabilities, $P_{RV}$, and the compiled proper-motion membership probabilities, $P_{PM}$. All LOS membership probabilities of our K2 targets have $P_{RV} \geq 95\%$. A total of 16 K2 stars have $P_{PM} > 75\%$, while three additional stars have 75% > $P_{PM} > 50\%$. Star IDW 27038 only has a $P_{RV}$ estimate. Essentially, all 20 stars can be considered as bona fide cluster members.

We checked both the full-frame K2 images and those from the Digitized Sky Survey (DSS1), to examine whether any of our light curves might be contaminated with light from neighbors. These can be seen in cutouts from both DSS1 and

---

9 Although additional stars could be added by relaxing our criteria—five more by allowing 0.55 < Θ < 0.75—we conservatively decided not to include them in this first paper. These stars also lie on the same sequence in the cluster CPD and do not alter our results.
Figure 2. Color–magnitude diagram for M67, with the periodic rotators highlighted (red). Only the single cluster members from GLM15 are displayed (black). The periodic spotted stars occupy the range $0.58 < B - V < 1.04$ i.e., $1.15 < M/M_\odot < 0.8$, on the main sequence. The rotator at $B-V = 0.58$ is the only binary in this sample. Two coincident stars at $B-V = 0.79$ are artificially separated in color. The two stars on the photometric equal-mass binary sequence are spectroscopically single cluster members.

K2 images of a $30'' \times 30''$ region centered on each star, and are included in the Appendix. Note that each K2 pixel is 3.98. The nearest neighbor, at a separation of $\sim 8''$, is 2.5 mag fainter than the K2 target EPIC 211398541 (=IDW 19034). Brighter neighbors can be found at distances exceeding 13'', and should not make significant contributions to the target’s light curve. Indeed, three bright neighbors (see Table 1) are K2 targets in their own right and their light curves are very different from those of our periodic stars, validating our claim.

3. RESULTS

3.1. The Rotators in the Color–Magnitude Diagram

M67 has a well-known and rich CMD, which we reproduce in Figure 2, displaying only the single cluster members from GLM15. The $(B-V, V)$ data plotted here are taken from GLM15, sourced mainly but not exclusively from Montgomery et al. (1993). (See also Sandquist 2004, and Yadav et al. 2008). The displayed region includes a richly populated main sequence which is the region of interest here, photometric binaries, the turnoff, subgiants, and the base of the giant branch. The 19 single and one binary (at $B-V = 0.58$) cluster members for which we have derived rotation periods are highlighted in this figure. The periodic rotators all lie on the cluster’s single or photometric binary sequence as expected. They cover the range $0.54 < (B-V)_0 < 1.00$, equivalent to $1.15 > M/M_\odot > 0.8$, encompassing stars with spectral types ranging from F8 to K4. We have used $E(B-V) = 0.04$, as recommended in the exhaustive study of Taylor (2007).

3.2. The Color–Period Diagram

The location of the 20 periodic cluster member stars in the corresponding color–period diagram (CPD) is displayed in

Figure 3. The periods are observed to be a function of stellar mass, with the bluer/higher-mass stars having shorter periods, and the lower-mass stars having longer periods. In fact, although the relationship seen in Figure 3 is less tight than, e.g., the equivalent one in the 2.5 Gyr-old cluster NGC 6819 (Meibom et al. 2015), the stars clearly follow the same trend of increasing period with redder color (decreasing mass) as the one observed initially in the Hyades (Radick et al. 1987), and subsequently in a succession of other well-studied open clusters, both younger and older and even field stars, as proposed in Barnes (2003, 2007). In these publications the shape of the mass dependence was proposed to be age-independent and represented by a function, $f = A(B-V)$, only of color. Although this was an adequate approximation a decade ago, it is not believed to be a completely satisfactory description at this time. See B10 for a more recent viewpoint. These M67 CPD data represent the cross-section of the $P = P(t, M)$ surface at the cluster age, $t \approx 4$ Gyr. The present-day Sun is very close to the mean curve defined by the M67 data points and lies marginally above the mean and median-isochrones (described below), implying that the Sun is likely slightly older than M67. In such CPDs, stars of a given mass move upward on almost vertical lines as they spin down steadily with age (Barnes et al. 2016). The solar-mass stars, defined as those with $0.60 \leq (B-V)_0 \leq 0.70$ (and ignoring the outliers\textsuperscript{10} IDW = 12030 = EPIC 211411477 at $P = 31.2$ d), have a mean rotation period of 25.8 d (median = 26 d and standard deviation $\sigma = 1.3$ d). At the current level of precision, this value is indistinguishable from the solar rotation period of 26.1 d (Donahue et al. 1996).

It should be noted that the bluer stars of our sample have systematically smaller variability amplitudes (in agreement

\textsuperscript{10} This star has a comparably bright neighbor, EPIC 211411722, at a distance of 14.88 (see Table 1).
with prior open cluster results), indicating that they have smaller fractional spotted areas, while the reddest stars are variable enough to be detectable even from the ground. Stars with spectral types F8-G0 are not detectably spotted. Similar variable enough to be detectable even from the ground. Stars with spectral types F8-G0 are not detectably spotted. Similar behaviors were noticed in the younger clusters NGC 6819 and NGC 6811 (see Meibom et al. 2011, 2015).

We are reporting rotation periods for 20 stars of the 106 GLM15 member stars outside the area of the central K2 superstamp. These are undoubtedly the M67 stars with both relatively large spot groups, and also those with rotational axes favorably inclined with respect to the Earth. The remainder of the 106 members include stars where spot evolution does not allow good period determination, those that are either just unfavorably inclined, and those that had insufficiently asymmetric spot distributions and/or smaller-than-detectable spot sizes during the K2 observations.

There are a half dozen additional periodic stars with lower variability levels among the 106 members. Although their light curves are less convincing than the ones reported here (at the current levels of light curve correction), they lie in the same regions of the CMD and CPD currently occupied by our sample. This fact informs us that the CPD displayed in Figure 3 is robust against the particular choice of variables displayed. Other researchers might construct M67 rotator samples using slightly different choices for individual stars and may choose different data reduction strategies. However, we opine that the CPD presented here is unlikely to be altered significantly by such choices.

Finally, we note that the $P = P(t, M)$ surface for M67 is expected to be intrinsically thinner than, for example, that of the 2.5 Gyr cluster NGC 6819, because rotational evolution is highly convergent (e.g., Kawaler 1988; Barnes & Kim 2010) under normal circumstances (i.e., for stars that are not located in close binary systems or are otherwise pathological). The measured surface presented here is wider. We attribute this scatter to the long rotation periods of the sample stars relative to the K2 observing baseline. In contrast, the availability of multiple quarters of Kepler data for NGC 6819 enabled multiple determinations of each star’s period (see Meibom et al. 2015) and the calculation of a corresponding mean stellar rotation period.

### 3.3. Rotational Age for the Cluster

Clearly all these stars, with or without determined rotation periods, have a single age equal to the cluster age, $\sim$4 Gyr (Demarque et al. 1992; VandenBerg & Stetson 2004; Bellini et al. 2010). However, by treating the individual measured stars independently (i.e., as field stars, each sampling the cluster age), we can examine the extent to which gyrochronology yields the same age for individual cluster stars and the uncertainties with which ages for similar field stars might be derivable.

We therefore proceed to derive rotational ages, $\tau_i$, for the individual periodic rotators in M67 from the periods, $P_i$. Various models may be used for this purpose, beginning with those of Endal & Sofia (1981) for solar-mass stars. We use the relationship

$$
\tau = \frac{\tau}{k_C} \ln \left( \frac{P}{P_0} \right) + \frac{k_I}{2\tau} \left( P^2 - P_0^2 \right)
$$

(1)

from B10 because of its prior success relative to other models in describing similar observations in a series of younger open clusters, including most recently the 400 Myr old cluster M48 (Barnes et al. 2015) and the 2.5 Gyr-old cluster NGC 6819 (Meibom et al. 2015).11 Here $P_0 = 1.1 \, d$, and $k_C = 0.646 \, d \, Myr^{-1}$, $k_I = 452 \, Myr^{-1} d^{-1}$ are two-dimensionless constants, retained unchanged from B10. (The dispersion from the range (0.12–3.4 d) of possible initial rotation periods is negligible by the age of M67.)

---

11 Lanzafame & Spada (2015) (see Brown 2014) have also shown that this model is better than others at describing the mass dependence of rotation. By including the turnover timescale, and therefore the Rossby number, $Ro$, this model also connects to chromospheric activity work by Noyes et al. (1984), and a body of dynamo-related work going back to at least Durand & Latour (1978).
timescales, \( \tau \), for each star were obtained by interpolating the (global) values in column five from Table 1 in Barnes & Kim (2010).\(^\text{12}\) from the corresponding \( B - V \)\(_0\) colors in GLM15. We have made one update: the rotational isochrone now takes into account the (small) blueward evolution of stars between the ZAMS and solar age.

The relevant rotational isochrones (sometimes called gyrochrones) are displayed in Figure 4. The mass dependence of the observations at the cluster age is clearly described satisfactorily by the mean and median rotational isochrones, indicating a rotational age of 4.2 Gyr (more below). We also display the initial condition used for the ZAMS and rotational isochrones for younger open clusters of representive ages where the B10 model provides good fits to the data. Because the rotation period evolution of stars in this diagram is almost exactly vertical (i.e., the color of a main sequence star hardly changes with age), this CPD succinctly displays how the rotation period for a field star can be used to derive its age.

The histogram of the rotational ages for the M67 stars is displayed by the red stripes in Figure 5. We obtain a distribution peaked at \( \sim 4 \) Gyr with all M67 periodic stars but one located in the interval \( 3.4 \) Gyr < \( Age < 5.3 \) Gyr, bracketing the mean and median cluster ages. A (B10) rotational age for M67 outside this range is essentially excluded. The single outlier is the star with \( P = 31.2 \) d which is only slightly redder than the Sun (see also Table 1). The mean and median values are, respectively, 4.15 Gyr and 4.28 Gyr, leading us to quote 4.2 Gyr as the B10 rotational age of the cluster. The standard deviation of the individual age measurements is 0.7 Gyr (=17%), which we take to represent the uncertainty that one might obtain for an FGK field star of similar age and metallicity from observations of similar quality.\(^\text{13}\) The comparison between the B10 model and the measured data points gives \( \chi^2_{red} = 2.35 \). This implies that we are definitely not overfitting the M67 CPD. On the other hand, if the model is a good one, this value could be interpreted to mean that the period errors are slightly underestimated.

In this context it should also be mentioned that there is a long history of rotational stellar models beginning with Endal & Sofia (1976), whose details and predictions are beyond the scope of this paper. Post-2010 alternatives to the model presented here include Lanzafame & Spada (2015), Gallet & Bouvier (2015), Johnstone et al. (2015), Matt et al. (2015), Brown (2014), Epstein & Pinsonneault (2014), and Spada et al. (2011). The models will undoubtedly be tested against these data in due course.

Let us now briefly consider the cluster as a whole. The standard error on the mean cluster age is \( 0.7/\sqrt{19} = 0.16 \) Gyr. But systematic errors could also add to the uncertainty in the rotational age of the cluster. For instance, a non-solar metallicity could conceivably affect the rotational age of the cluster, especially as gyrochronology is currently calibrated only for solar metallicity stars. Fortunately, this is likely negligible because high-resolution spectroscopic studies of M67 (e.g., Randich et al. 2006, and Jacobson et al. 2011) find [Fe/H] values essentially indistinguishable from solar. Finally, there is the reddening uncertainty. Again, this cannot be very large because the cluster itself is off the Galactic plane, and thus barely reddened, with \( E(B - V) = 0.04 \). Cautious investigators such as Brucalassi et al. (2014) consider values as distant as \( E(B - V) = 0.02 \). However, Taylor (2007) insists on a reddening uncertainty of only 0.004 mag and Vandenberg & Stetson (2004) believe the reddening to be established to an uncertainty of only \( \pm 0.005 \). Such a change would perturb the cluster gyrochronology age by only \( \pm 0.05 \) Gyr. Adding this in quadrature to the standard error on the mean gives a total uncertainty of 0.17 Gyr, which we round to 0.2 Gyr and adopt as the uncertainty on the B10 rotational age of M67, listing it finally as 4.2 \( \pm 0.2 \) Gyr.

The results reported here accord well with prior work on M67. Giampapa et al. (2006) have studied the chromospheric emission of M67 stars, confirming a mean emission similar to that of the Sun but with greater excursions from the mean. We have (re)calculated stellar ages from their measurements using the activity-age calibration of Mamajek & Hillenbrand (2008), retaining only the 50 single cluster members of GLM15, and present this histogram for comparison with the rotational ages in Figure 5. This chromospheric age distribution has mean and median values of 4.2 Gyr and 3.95 Gyr, respectively, and a standard deviation of 1.6 Gyr (=38%), in agreement with prior knowledge. The chromospheric age of the cluster is therefore 4.1 \( \pm 0.23 \) Gyr, where the uncertainty quoted is solely the standard error on the mean. This value is identical to the rotational age to within the uncertainties.

4. CONCLUSIONS

The rotation periods of cool (FGK) single member stars in M67 define a sequence in the CPD reminiscent of that discovered first in the Hyades open cluster. The Sun lies marginally above the sequence in the M67 CPD and on the same \( P = P(t, M) \) surface defined by prior open cluster observations. This fact strengthens the solar–stellar connection.

The location of the rotational sequence in the CPD is in agreement with the predictions of prior (semi)empirical rotational models, implying that reliable rotational ages can be derived for solar metallicity dwarfs up to solar age, and likely up to the main sequence turnoff.

The gyro ages of the individual cluster members have a standard deviation of 0.7 Gyr (=17%), suggesting that similar age errors are attainable with \( K2 \) data for equivalent field stars (e.g., planet hosts), provided their surfaces are sufficiently asymmetrically spotted and spot evolution is not severe enough to prevent period determination. The gyro age for M67 as a whole is 4.2 \( \pm 0.2 \) Gyr, with the uncertainty originating primarily in the period determination errors, and to a lesser extent from reddening and metallicity uncertainties.

Finally, we note that the variability of Sun-like stars is at a similar level as that of the (quiet-to-active) Sun and that two major spot groups at widely different longitudes are evident in 70% of the light curves in the sample reported here.

We acknowledge the anonymous referee for a careful and helpful report. We are grateful to the German and US taxpayers for supporting this work, and to NASA and \( K2 \) for making the data publicly available.

Facilities: Kepler, \( K2 \).
Figures 6–12 display the light curves for the 20 periodic stars presented in this paper, together with the associated smoothed power spectra for the four principal period search methods used. Figures 13 and 14 show cutouts for each of these stars from the digitized sky survey and the final full-frame K2 image.

**Figure 6.** Light curves and results from four period analysis methods with the abscissae marked at 5 d intervals and the final period indicated. The ordinate for the light curves indicates 1 mmag intervals, while those for the PDM, SL, GL, and AC panels give the Θ statistic (0 to 1), the deviation of the measured string length (−35 to 15), the natural logarithm of the posterior probability of a given period (with upper limit $P = 1$), and the autocorrelation of the timeseries (−0.5 to 1), respectively.
Figure 7. Light curves and results from four period analysis methods with the abscissae marked at 5 d intervals and the final period indicated. The ordinate for the light curves indicates 1 mmag intervals, while those for the PDM, SL, GL, and AC panels give the $\Theta$ statistic (0 to 1), the deviation of the measured string length (−35 to 15), the natural logarithm of the posterior probability of a given period (with upper limit $P = 1$), and the autocorrelation of the timeseries (−0.5 to 1), respectively.
Figure 8. Light curves and results from four period analysis methods with the abscissae marked at 5 d intervals and the final period indicated. The ordinate for the light curves indicates 1 mmag intervals, while those for the PDM, SL, GL, and AC panels give the $\Theta$ statistic (0 to 1), the deviation of the measured string length (−35 to 15), the natural logarithm of the posterior probability of a given period (with upper limit $P = 1$), and the autocorrelation of the timeseries (−0.5 to 1), respectively.
Figure 9. Light curves and results from four period analysis methods with the abscissae marked at 5 d intervals and the final period indicated. The ordinate for the light curves indicates 1 mmag intervals, while those for the PDM, SL, GL, and AC panels give the $\Theta$ statistic (0 to 1), the deviation of the measured string length (−35 to 15), the natural logarithm of the posterior probability of a given period (with upper limit $P = 1$), and the autocorrelation of the timeseries (−0.5 to 1), respectively.
Figure 10. Light curves and results from four period analysis methods with the abscissae marked at 5 d intervals and the final period indicated. The ordinate for the light curves indicates 1 mmag intervals, while those for the PDM, SL, GL, and AC panels give the $\Theta$ statistic (0 to 1), the deviation of the measured string length (−35 to 15), the natural logarithm of the posterior probability of a given period (with upper limit $P = 1$), and the autocorrelation of the timeseries (−0.5 to 1), respectively.
Figure 11. Light curves and results from four period analysis methods with the abscissae marked at 5 d intervals and the final period indicated. The ordinate for the light curves indicates 1 mmag intervals, while those for the PDM, SL, GL, and AC panels give the $\Theta$ statistic (0 to 1), the deviation of the measured string length (-15 to 15), the natural logarithm of the posterior probability of a given period (with upper limit $P = 1$), and the autocorrelation of the timeseries (-0.5 to 1), respectively.
Figure 12. Light curves and results from four period analysis methods with the abscissae marked at 5 d intervals and the final period indicated. The ordinate for the light curves indicates 1 mmag intervals, while those for the PDM, SL, GL, and AC panels give the $\Theta$ statistic (0 to 1), the deviation of the measured string length (−35 to 15), the natural logarithm of the posterior probability of a given period (with upper limit $P = 1$), and the autocorrelation of the timeseries (−0.5 to 1), respectively.
Figure 13. 30″ × 30″ cutouts from the digitized sky survey (DSS1) image of the M67 cluster region.
Figure 14. 30'' × 30'' cutouts from the final full-frame K2 image of the M67 cluster region.
REFERENCES

Allegre, C. J., Manhes, G., & Gopel, C. 1995, GeCoA, 59, 1445
Baliunas, S. L., Donahue, R. A., Soon, W. H., et al. 1995, ApJ, 438, 269
Baliunas, S. L., Sokoloff, D., & Soon, W. H. 1996, ApJ, 457, 99
Barnes, S. A. 2003, ApJ, 586, 464
Barnes, S. A. 2007, ApJ, 669, 1167
Barnes, S. A. 2010, ApJ, 722, 222 (B10)
Barnes, S. A., & Kim, Y.-C. 2010, ApJ, 721, 675
Barnes, S. A., Spada, F., & Weingrill, J. 2016, AN, in press
Barnes, S. A., Weingrill, J., Granzer, T., Spada, F., & Strassmeier, K. G. 2015, A&A, 583, 73
Bellini, A., Bedin, L. R., Piotto, G., et al. 2010, A&A, 513, A50
Bethe, H. A. 1939, PhRv, 55, 434
Brown, T. M. 2014, ApJ, 789, 101
Brun, A. S., Garcia, R. A., Houdek, G., Nandy, D., & Pinsonneault, M. 2015, SSRv, 196, 303
Delorme, P., Cameron, A. C., Hebb, L., et al. 2011, MNRAS, 413, 2218
Demarque, P. D., Green, E. M., & Guenther, D. B. 1992, AJ, 103, 151
Donahue, R. A. 1998, in ASP Conf. Ser. 154, Tenth Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, ed. R. A. Donahue, & J. A. Bookbinder (San Francisco, CA: ASP), 1235
Donahue, R. A., Saar, S., & Baliunas, S. L. 1996, ApJ, 466, 384
Durney, B. R., & Latour, J. 1978, GApFD, 9, 241
Dworetsky, M. M. 1983, MNRAS, 203, 917
Eberhard, G., & Schwarzschild, K. 1913, ApJ, 38, 292
Endal, A. S., & Sofia, S. 1976, ApJ, 210, 184
Epstein, C., & Pinsonneault, M. 2014, ApJ, 780, 159
Gallet, F., & Bouvier, J. 2015, A&A, 577, 98
Geller, A., Latham, D. W., & Mathieu, R. D. 2015, AJ, 150, 97 (GLM15)
Giammara, M. S., Hall, J. C., Radick, R. R., & Baliunas, S. L. 2006, ApJ, 651, 444
Gregory, P. C. 1999, ApJ, 520, 361
Gregory, P. C., & Loredo, T. J. 1992, ApJ, 398, 146
Hale, G. E., & Ellerman, F. 1904, ApJ, 19, 41
Johnstone, C. P., Guedel, M., Brott, I., & Lucfntinger, T. 2015, A&A, 577, A28
Kawaler, S. D. 1988, ApJ, 333, 236
Kawaler, S. D. 1989, ApJ, 343, 65
Kraft, R. P. 1967, ApJ, 150, 551
Kron, G. E. 1947, PASP, 59, 261
Lanzafame, A. C., & Spada, F. 2015, A&A, 584, 30
Lockwood, G. W., Henry, G. W., Hall, J. C., & Radick, R. R. 2013, in ASP Conf. Ser. 472, New Quests in Stellar Astrophysics III, ed. M. Chavez et al. (San Francisco, CA: ASP), 203
Mamajek, E., & Hillenbrand, L. A. 2008, ApJ, 687, 1264
Mihalas, D. 1981, in Proc. Solar Instrumentation: What’s next?, ed. R. B. Dunn (New Mexico), 193
Montgomery, K. A., Marschall, L. A., & Janes, K. A. 1993, AJ, 106, 181
Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Parker, E. N. 1958, ApJ, 128, 664
Pinsonneault, M. H., Kawaler, S., Sofia, S., & Demarque, P. 1989, ApJ, 338, 424
Radick, R. R., Thompson, D. T., Lockwood, G. W., Duncan, D. K., & Baggett, W. E. 1987, ApJ, 321, 459
Randich, S., Sestito, P., Primas, F., Pallavicini, R., & Pasquini, L. 2006, A&A, 450, 557
Sandage, A. S. 1962, ApJ, 135, 349
Soderblom, D. R., Duncan, D. K., & Johnson, D. R. H. 1991, ApJ, 375, 722
Skumanich, A. 1972, ApJ, 171, 565
Sukhawat, M. 2016, ApJ, 823:16 (16pp), 2016 May 20
Barnes et al.

The Astrophysical Journal, 823:16 (16pp), 2016 May 20

16