ROTATING STARS FROM *KEPLER* OBSERVED WITH *GAIA DR1*

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**ABSTRACT**

Astrometric data from the recent *Gaia* Data Release 1 have been matched against the sample of stars from *Kepler* with known rotation periods. A total of 1299 bright rotating stars were recovered from the subset of *Gaia* sources with good astrometric solutions, most with temperatures above 5000 K. From these sources, 894 were selected as lying near the main sequence using their absolute G-band magnitudes. These main-sequence stars show a bimodality in their rotation period distribution, centered roughly around a 600 Myr rotation isochrone. This feature matches the bimodal period distribution found in cooler stars with *Kepler*, but was previously undetected for solar-type stars due to sample contamination by subgiants. A tenuous connection between the rotation period and total proper motion is found, suggesting that the period bimodality is due to the age distribution of stars within ~300 pc of the Sun, rather than a phase of rapid angular momentum loss. This work emphasizes the unique power for understanding stellar populations that is created by combining temporal monitoring from *Kepler* with astrometric data from *Gaia*.

**Key words:** stars: general – stars: kinematics and dynamics – stars: rotation

1. INTRODUCTION

The *Kepler* mission (Borucki et al. 2010) has enabled the first studies of rotation periods for large ensembles of field stars. The fundamental stellar property of rotation has been measured for over 30,000 stars using the high-cadence *Kepler* light curves, tracing the periodic or quasi-periodic modulations in brightness as cool starspots rotate in and out of view (Reinhold et al. 2013; McQuillan et al. 2014). The seminal work by Skumanich (1972) connected stellar rotation and age via angular momentum loss, leading to a technique for estimating age known as gyrochronology. At present, ages determined by gyrochronology are accurate to ~10% in the best cases (young solar-type stars). Determining robust ages for field stars may soon be possible by calibrating gyro-isochrones to stellar clusters and asteroseismic samples, and by using improved models of angular momentum loss (e.g., Angus et al. 2015; van Saders et al. 2016).

McQuillan et al. (2013) discovered a bimodal period distribution for M dwarfs in the *Kepler* field, which was subsequently confirmed to exist for K dwarfs as well (McQuillan et al. 2014). However, this bimodality had never been observed in any other study of stellar rotation periods, including stellar clusters at a variety of ages, nor was it detected in the *Kepler* stars at higher temperatures ($T_{\text{eff}} > 5000$ K). While binary stars and multiple-period systems may be contaminating the sample of rotation periods for *Kepler* field stars, McQuillan et al. (2014) found that the presence of such interlopers could not adequately explain the bimodal period distribution. Currently favored explanations for this feature are (1) a discontinuous age distribution for nearby stars, as was suggested for very nearby *Hipparcos* stars by Hernandez et al. (2000), or (2) a previously unknown phase of rapid angular momentum loss for low-mass stars, similar to the “Vaughan–Preston” gap seen in chromospheric activity indicators (Vaughan & Preston 1980). As independent age indicators for these field stars are often non-existent, and both scenarios deal with physical mechanisms that are not currently understood with precision, a definitive explanation has not been found.

Astrometric data from the *Gaia* mission (Gaia Collaboration 2016) can help shed light on this mystery of stellar population. By measuring distances via stellar parallax for these rotating stars, the *Kepler–Gaia* sample can separate single main-sequence dwarfs from binary stars or evolved stars such as subgiants, and will help calibrate fundamental properties of *Kepler* stars, such as log(g) (Creevey et al. 2013). Galactic kinematics from *Gaia* will also provide an additional proxy for age, and enable searches for substructure in ages of field stars such as from moving groups. The *Gaia* data will also enable a measurement of the star formation history of the disk from both cooling sequences of white dwarfs (Carrasco et al. 2014; Gaensicke et al. 2015) and models of color–magnitude diagrams (Bertelli et al. 1999).

In this paper I demonstrate the utility of combining temporal properties derived from *Kepler* light curves with the preliminary astrometric solutions from *Gaia* Data Release 1 (hereafter DR1, Lindegren et al. 2016). This combined sample allows improved selection of main-sequence stars and reveals previously undetected structure in the rotation period distribution for solar-type stars.

2. THE *KEPLER–GAIA* DATA

Rotation periods in this study come from McQuillan et al. (2014), who performed an autocorrelation function analysis of *Kepler* stars cooler than 6500 K that had at least ~2 yr of observation. The periods recovered from this approach generally agree very well with those found via Lomb–Scargle periodograms (e.g., Reinhold et al. 2013; Aigrain et al. 2015). Sources with multiple distinct periods, such as from binary systems with two spotted stars (e.g., Lurie et al. 2015) are detected by McQuillan et al. (2014), but are not included in the following analysis.

The *Gaia* DR1 provides astrometric positions for over $10^9$ sources from the first year of observation with *Gaia*. The Tycho–*Gaia* Astrometric Solution (TGAS) measures improved proper motions and parallaxes for 2 million nearby, bright
sources by extending the astrometric solutions from Tycho and Hipparcos. While the TGAS data are not a complete astrometric survey, and have possible systematics in the reported parallaxes (Lindegren et al. 2016; Stassun & Torres 2016), they represent a significant improvement in the astrometry and kinematics available for stars in the Kepler field.

Using the CDS X-Match service, I cross-matched the available catalogs from these two surveys. A default cross-match radius of 5 arcsec was used. A total of 33,855 stars were found in the cross match between these catalogs, which is 99.5% of the sample from McQuillan et al. (2014). The small number of stars not recovered from McQuillan et al. (2014) may be missed because of source confusion within the matching radius. A subset of 1299 objects were recovered in the TGAS sample. Very few K and M dwarfs were recovered in that sample because of its brightness limits. Future releases of Gaia data will provide full astrometric solutions for nearly all Kepler stars. The rotation periods versus stellar effective temperatures for the Kepler–Gaia matched stars are shown in Figure 1.

3. SELECTING MAIN-SEQUENCE STARS

Though McQuillan et al. (2014) attempted to measure periods only for dwarf stars, the sample of Kepler–Gaia matched stars contains both main-sequence dwarfs and evolved stars (giants or subgiants). Previous studies have shown that significant contamination by giants or subgiants can affect the implied variability properties of dwarf stars (Ciardi et al. 2011; Mann et al. 2012). Therefore to properly understand the nature of the period distribution and its implications for age-dating field stars, a robust sample of main-sequence stars must be selected.

Faint stars were removed by requiring sources to have G-band flux errors <1%. To ensure accurate distances, and therefore luminosities, parallaxes were required to have errors <0.4 mas. These cuts left a total of 894 stars from the Kepler–TGAS-matched sample (68%). The Hertzsprung–Russell (H–R) diagram for these stars is shown in Figure 2, with each point colored by its Kepler-measured rotation period. Example isochrones from the grid of Bressan et al. (2012) are shown for two ages. A systematic offset of ~0.5 mag is found between the measured absolute G-band and the isochrone’s main sequence. This offset is likely due to calibration differences between the nominal and actual G-band (A. Brown 2016, private communication).

The H–R–period diagram in Figure 2 shows stars with a range of evolutionary states, and could help to test models of the evolution of post-main-sequence angular momentum (e.g., do Nascimento et al. 2012). Outliers in this diagram are either due to erroneous crossmatching in the Kepler and Gaia catalogs or represent interesting systems such as rare binary star configurations or stars that have undergone mergers or ingested giant planets (Massarotti 2008; Tayar et al. 2015). For example, examination of the 2MASS (Skrutskie et al. 2006) image on SIMBAD for the rapidly rotating star at $T_{\text{eff}} = 4500$ K, $M_G = 4.5$ mag, $P_{\text{rot}} = 0.652$ day, in Figure 2 (KIC 07957709) shows
that this source appears to be highly contaminated with three point sources clustered within ~10 arcsec, likely leading to an erroneous position in the H-R diagram, and possibly incorrect variability measurements with Kepler. Investigating all such outliers in Figure 2 is beyond the scope of this work, but these targets are worth further study because they may reveal new physics.

Main-sequence stars were selected using a simple cut around the 300 Myr isochrone. Given the systematic offset of ~0.5 mag between the 300 Myr isochrone and the observed $M_G$ values, a fairly wide band of stars ($0 \leq \Delta M_G \leq 1$) was selected as being “close to the main sequence.” The final sample included 440 stars. This simplistic cut is not a robust separator between dwarfs and giants, nor between single and binary stars, but serves to select a sample of mostly main-sequence stars for the illustrative purpose of this work. More precise selection will require an improved isochrone track, as well as updated parallaxes from the full Gaia DR2.

4. EXTENDING THE SPIN-DOWN GAP

A bimodal period distribution was first discovered by McQuillan et al. (2013) for Kepler M dwarfs; they found a dearth of objects with periods around ~25 days. Follow-up work by McQuillan et al. (2014) found that this bimodality extended to K dwarfs, up to $T_{eff} \sim 5500$ K. Figure 3 shows the rotation period distribution for the final sample of 440 likely main-sequence stars. The bimodality appears to extend smoothly through to the hottest stars in this sample.

While these periods for field stars were robustly measured by McQuillan et al. (2014) and others, the bimodality did not appear in previous Kepler work due to the high rate of contamination by subgiants for these bluer, hotter stars. 414 rotating stars had acceptable photometric and parallax uncertainties in TGAS, but were culled from this sample for having $M_G$ luminosities higher than the main-sequence cut in Section 3 above. Note that distributions of log g values from the Kepler Input Catalog (Brown et al. 2011) for both the main-sequence and subgiant stars were not statistically different.

The minimum in the bimodal period distribution in Figure 3 can be traced using a gyrochronology isochrone (colloquially known as a “gyrochrone”). Many different studies have produced competing gyrochrones models, each with unique morphologies in the regimes of hot and cool star (e.g., Barnes 2007; Mamajek & Hillenbrand 2008; Meibom et al. 2011; Angus et al. 2015). A 600 Myr gyrochrone from Meibom et al. (2011), converted from $B - V$ color to temperature using the transformation from Sekiguchi & Fukugita (2000), was determined by eye to approximately trace the period minima from 3500 to 6000 K. As shown in Figure 3, this model (as with most gyrochronology models) turns down in period sharply for stars hotter than ~6000 K. A log–linear extrapolation of the 600 Myr gyrochrone at 6000 K continues to trace the period bimodality up to 6500 K, and roughly traces a line of constant Rossby number if one assumes a local convective turnover timescale such as from Barnes & Kim (2010).

The difference (in log period) between the observed rotation and the 600 Myr gyrochrone is shown in Figure 4. Despite combining stars of all temperatures, the bimodality is clearly seen in this log period space for the 440 likely main-sequence stars. A two-Gaussian model was fit to these data, which found peaks in the two distributions of $-0.19 \pm 0.01$ and $0.21 \pm 0.01$ dex. 262 stars had periods longer than the gyrochrone model (right peak) and 178 shorter than the model (left peak). This is in contrast to the overall results from McQuillan et al. (2013) who found nearly equal numbers of M dwarfs in the fast and slow rotating groups, but is in general agreement with their sample of stars with non-zero proper motions. The whole sample of 894 stars with good TGAS detections does not show this bimodality in Figure 4, demonstrating the importance of culling subgiants from the sample.

The explanation for the bimodal period distribution favored by McQuillan et al. (2013) was an age effect, with nearby stars having a bimodal star formation history. This explanation was bolstered by their observation that stars in the two period groups have differing distributions of proper motions, indicating that they belong to kinematically separate groups. This measurement is replicated in Figure 5, which shows the total

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.pdf}
\caption{Rotation period vs. temperature for TGAS-matched stars near the isochrone main sequence (blue circles). The full Kepler–Gaia matched sample is shown for reference (small black dots). A bimodality in rotation periods initially discovered for M dwarfs by McQuillan et al. (2013) extends over the full range of temperatures in the Kepler–Gaia main-sequence sample shown here. A 600 Myr gyrochronology isochrone (gyrochrone) of Meibom et al. (2011) traces the bimodality midpoint up to 6000 K (red solid line), but deviates from the isochrone sharply to ~6200 K (red dotted line). A log–linear extrapolation of the isochrone at 6000 K to 6500 K (red dashed line) continues to track the bimodality to higher temperatures, and roughly follows a line of constant Rossby number.}
\end{figure}
proper motion distribution for stars above and below the 600 Myr gyrochrone. Stars above the gyrochrone (slower rotators, nominally older) have a median total proper motion of 15.4 mas yr\(^{-1}\), while those below (faster rotators, younger) have a median of 11.3 mas yr\(^{-1}\). This difference in kinematics versus rotation period is in the same direction as observed by McQuillan et al. (2013). The Kolmogorov–Smirnov statistic for these two samples is 0.14, which does not rule out the null hypothesis that they are drawn from the same distribution. The slower rotating sample (black in Figure 5) appears to have a bimodal distribution in proper motion, indicating possibly significant contamination from a younger population with lower proper motion that is consistent with the rapidly rotating stars. Figure 5 also shows the proper motion as a function of the residual rotation period defined in Figure 4. Despite the small sample size, this distribution highlights the complex relationship between ages derived from gyrochronology and those from galactic kinematics, including bimodal structure for the proper motion of more slowly rotating stars. Further investigation of rotation and kinematics of nearby stars using larger samples from future Gaia data releases is needed.

5. DISCUSSION

Using a combination of data from Kepler and Gaia DR1, I have explored the rotation period distribution for 440 nearby main-sequence stars. A bimodal rotation period distribution has been found in stars with temperatures ranging from 5000 to 6500 K. This feature matches that found in cooler stars from Kepler, but was only revealed thanks to the enhanced ability to distinguish dwarfs from subgiants using Gaia data. A tenuous difference in the TGAS total proper motion for stars in the fast and slowly rotating groups is found, which is in agreement with the findings for cool stars by McQuillan et al. (2013).

While a definitive explanation for this period bimodality has not been reached, the findings to date seem to favor stellar ages as the cause. In this scenario the star formation history for nearby stars would be dominated by two epochs of star formation—one short event centered at a few hundred million years and one long event centered at a few billion years (slightly younger than the Sun). It is also worth noting that the space volume probed by the TGAS sample investigated here is very similar to that covered by the temperature-selected sample of cool stars in McQuillan et al. (2013). The median parallax distance for stars in this work is 285 pc, while the median isochrone distance for the K and M dwarfs is \(\sim 216\) pc. This points to the period distribution being a localized age artifact. Determining how localized this age distribution is, and whether it can be confirmed for stars across the H-R diagram including giants, is a key goal for future Gaia data releases.

The period bimodality may yet be a manifestation of the “Vaughan–Preston” gap observed in chromospheric activity indicators from solar-type stars. Such a feature has also been discussed for rotating stars by Kado-Fong et al. (2016). Given that the mass range for the bimodality explored here and in McQuillan et al. (2014) covers stars with solar-type dynamos (those having a tachocline, late F through early M), such a model cannot be fully ruled out at this time. Though there have been many studies of rotation for cool stars (e.g., Irwin et al. 2011; Newton et al. 2016; Stelzer et al. 2016) too few rotation periods have been measured for stars across the “fully convective boundary” (\(T_{\text{eff}} < 3000\) K, spectral type \(\sim \text{M}4\)) to tell whether the bimodal period feature continues to lower temperatures,
which would support the model of age distribution. If the bimodality is due to stars crossing a phase of rapid angular momentum evolution, we would expect to see it in stellar clusters at or near the critical age. The lack of this feature in the clusters observed to date could be due to no cluster being close enough to the critical age, which the gyrochrone in Figure 3 shows is near 600 Myr. Further studies of rotation periods for stars in intermediate-age open clusters (e.g., the Hyades) may help solve this mystery (e.g., Douglas et al. 2014).

Finally, this exploratory work has highlighted the utility of using astrometric data from Gaia combined with detailed light-curve statistics from Kepler to reveal hidden substructure in the properties of field stars. Looking forward to the astrometric precision of future Gaia data releases, this combination will be effective at separating dwarf stars from subgiants for nearly the entire Kepler and K2 databases, and will enable accurate age maps for field stars.

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REFERENCES

Aigrain, S., Llama, J., Ceillier, T., et al. 2015, MNRAS, 450, 3211
Angus, R., Aigrain, S., Foreman-Mackey, D., & McQuillan, A. 2015, MNRAS, 450, 1787
Barnes, S. A. 2007, ApJ, 669, 1167
Barnes, S. A., & Kim, Y.-C. 2010, ApJ, 721, 675
Bertelli, G., Bressan, A., Chiosi, C., & Vallenari, A. 1999, BaIIA, 8, 271
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Sci, 327, 977
Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127
Brown, T. M., Latham, D. W., Everett, M. E., & Esquerdo, G. A. 2011, AJ, 142, 112
Carrasco, J. M., Catalán, S., Jordi, C., et al. 2014, A&A, 565, A11
Ciardi, D. R., von Braun, K., Bryden, G., & et al. 2011, AJ, 141, 108
Creevey, O. L., Thévenin, F., Basu, S., et al. 2013, MNRAS, 431, 2419
do Nascimento, J.-D., da Costa, J. S., & Castro, M. 2012, A&A, 548, L1
Douglas, S. T., Agüeros, M. A., Covey, K. R., et al. 2014, ApJ, 795, 161
Gaensicke, B., Tremblay, P.-E., Barstow, M., et al. 2015, arXiv:1506.02653
Gaia Collaboration 2016, A&A, 595, 1
Hernandez, X., Valls-Gabaud, D., & Gilmore, G. 2000, MNRAS, 316, 605
Irwin, J., Berta, Z. K., Burke, C. J., et al. 2011, ApJ, 727, 56
Kado-Fong, E., Williams, P. K. G., Mann, A. W., et al. 2016, ApJ, 833, 281
Lindegren, L., Lammers, U., Bastian, U., et al. 2016, arXiv:1609.04303
Lurie, J. C., Davenport, J. R. A., Hawley, S. L., et al. 2015, ApJ, 800, 95
Mamajek, E. E., & Hillenbrand, L. A. 2008, ApJ, 687, 1264
Mann, A. W., Gaidos, E., Lépine, S., & Hilton, E. J. 2012, ApJ, 753, 90
Massarotti, A. 2008, AJ, 135, 2287
Matt, C. F., Massa, L., Gubskaya, A. Y., & Knoll, E. 2011, JChemEd, 88, 67
McQuillan, A., Mazeh, S., & Meibom, S., Barnes, S. A., Latham, D. W., et al. 2011, ApJL, 733, L9
Newton, E. R., Irwin, J., Charbonneau, D., et al. 2016, ApJ, 821, 93
Reinhold, T., Neiner, C., & Basri, G. 2013, A&A, 560, A4
Sekiguchi, M., & Fukugita, M. 2000, AJ, 120, 1072
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Skumanich, A. 1972, ApJ, 171, 565
Stassun, K. G., & Torres, G. 2016, arXiv:1609.05390
Stelzer, B., Damasso, M., Scholz, A., & Matt, S. P. 2016, MNRAS, 463, 1844
Tayar, J., Ceillier, T., García-Hernández, D. A., et al. 2015, ApJ, 807, 82
van Saders, J. L., Ceillier, T., Metcalfe, T. S., et al. 2016, Natur, 529, 181
Vaughan, A. H., & Preston, G. W. 1980, PASP, 92, 385