DRAFT VERSION OCTOBER 18, 2016
Preprint typeset using LaTeX style AASTeX6
With modifications by David W. Hogg and Daniel Foreman-Mackey

ROTATING STARS FROM *Kepler* OBSERVED WITH GAIA DR1

JAMES R. A. DAVENPORT[1,2]

[1]Department of Physics & Astronomy, Western Washington University, 516 High St., Bellingham, WA 98225, USA

[2]NSF Astronomy and Astrophysics Postdoctoral Fellow

ABSTRACT

Astrometric data from the recent Gaia Data Release 1 has been matched against the sample of stars from *Kepler* with known rotation periods. A total of 1,299 bright rotating stars were recovered from the subset of Gaia sources with good astrometric solutions, most with temperatures hotter than 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 from 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 the period bimodality is due to the age distribution of stars within ∼300pc of the Sun, rather than a phase of rapid angular momentum loss. This emphasizes the unique power for stellar populations studies of combining temporal monitoring from *Kepler* with astrometric data from Gaia

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 30k 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 an age estimating technique known as gyrochronology. At present, ages determined by gyrochronology are accurate to ∼10% in the *best* cases (young solar-type stars). With rotation now being routinely measured, it is hoped a new ability of determining robust ages for field stars will be possible by calibrating gyro-isochrones, and (e.g. Angus et al. 2015; van Saders et al. 2016).

Curiously, in studying the rotation periods for M dwarfs in the *Kepler* field, McQuillan et al. (2013) discovered a bimodal period distribution, which was subsequently confirmed to exist up to K dwarfs in the *Kepler* field by McQuillan et al. (2014). However, this 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 hotter temperatures ($T_{eff} > 5000$). While binary stars and multiple-period systems may be contaminating the rotation period sample for *Kepler* field stars, McQuillan et al. (2014) found they could not adequately explain the bimodal period distribution. Currently favored explanations for this feature are 1) a non-continuous age distribution for nearby stars, as was suggested with 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 stellar population mystery. 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 age-proxy, and allow for searches of substructure in field star ages such as from moving groups. The Gaia data will also enable a measurement of the star formation history of the disk from both white dwarf cooling sequences (Carrasco et al. 2014; Gaensicke et al. 2015) and color-magnitude diagram models (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 Auto-Correlation Function analysis of *Kepler* stars cooler than 6500 K that had at least ∼2 years 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

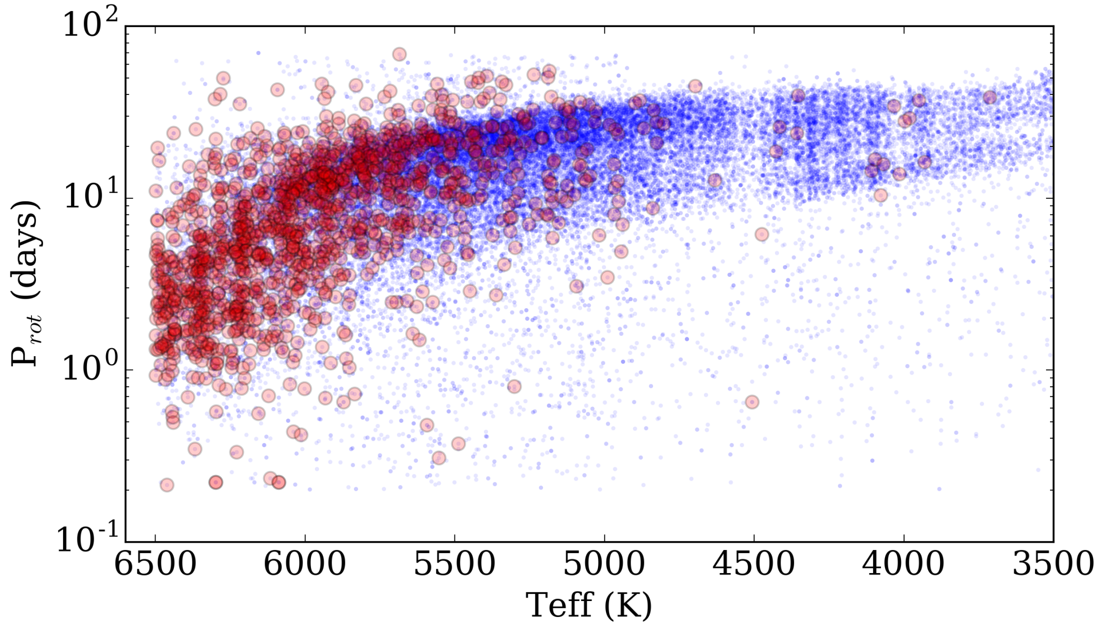

Figure 1. Rotation period distribution for 33,855 *Kepler* stars from McQuillan et al. (2014) with detections in Gaia DR1 (blue dots). The period bimodality can be seen most clearly for stars with $T_{eff} < 4000$ K as a dearth of sources with periods of ∼20 days, but extends to at least $T_{eff} \sim 5500$ K according to McQuillan et al. (2014). The subsample of 1,299 nearby objects found in TGAS are highlighted (red circles), and are mostly hotter stars due to the faint limit of the TGAS sample.

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 Data Release 1 (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 (Stassun & Torres 2016), they represent a significant improvement in the astrometry and kinematics available for stars in the *Kepler* field thanks to the precision of Gaia.

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 cross match between these catalogs, 99.5% of the sample from McQuillan et al. (2014). A subset of 1,299 objects were recovered in the TGAS sample. Due to the brightness limits of the TGAS sample very few K and M dwarfs were recovered in the TGAS sample. Future releases of Gaia data will ostensibly 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.

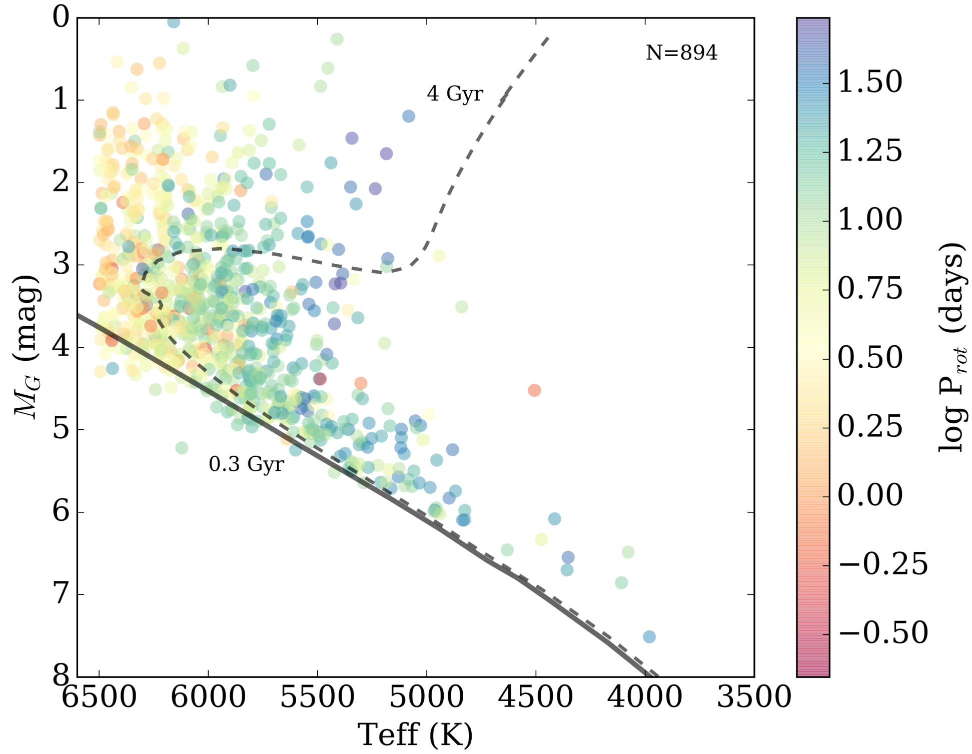

Figure 2. Hertzsprung–Russell (HR) diagram using temperatures from McQuillan et al. (2014) and Gaia DR1 G-band absolute magnitudes for the 894 stars that pass photometric and parallax quality cuts described in the text. Points are colored by their measured *Kepler* rotation periods. Two isochrones from Bressan et al. (2012) are shown, with ages of 300 Myr and 4 Gyr (solid and dashed lines).

3. SELECTING MAIN SEQUENCE STARS

first we create the HR diagram, using the absolute Gaia magnitudes from the TGAS parallaxes, and the temperatures reported from McQ14

4. EXTENDING THE SPIN-DOWN GAP

this feature first observed in rotation period by McQuillan et al. (2013) for M dwarfs

here we show it appears to extended to nearby higher mass stars in the *Kepler* field.

the reason this feature did not appear in earlier *Kepler* studies is the inability to select main sequence stars from turn-off or subgiants using the KIC

5. DISCUSSION

median distance of K/M stars ($T_{eff} > 4000$ K) is ∼216 pc, using isochrone median distance for the TGAS-matched sample (blue points) is very close, 285 pc, so also sampling just the most local volume. this points to the effect being localized around

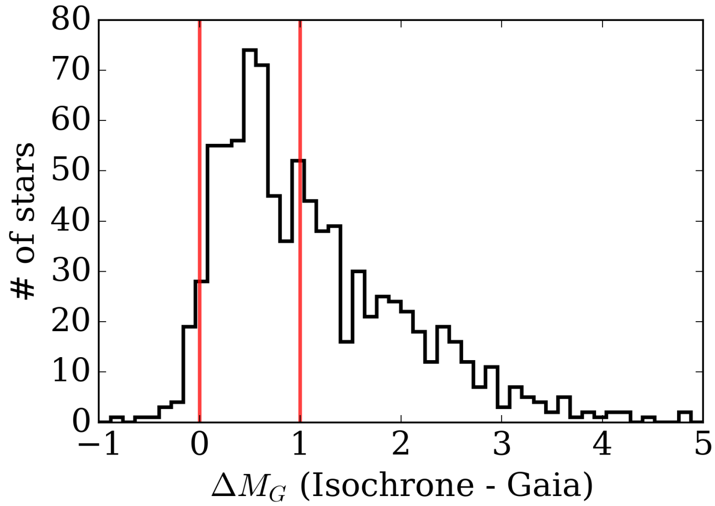

Figure 3. Distribution of differences between the Gaia DR1 G absolute magnitudes and values for main sequence stars from the 300 Myr isochrone shown in Figure 2. The range of sources selected near the single star main sequence (red lines) may have additional contamination due to dust extinction and binary companions.

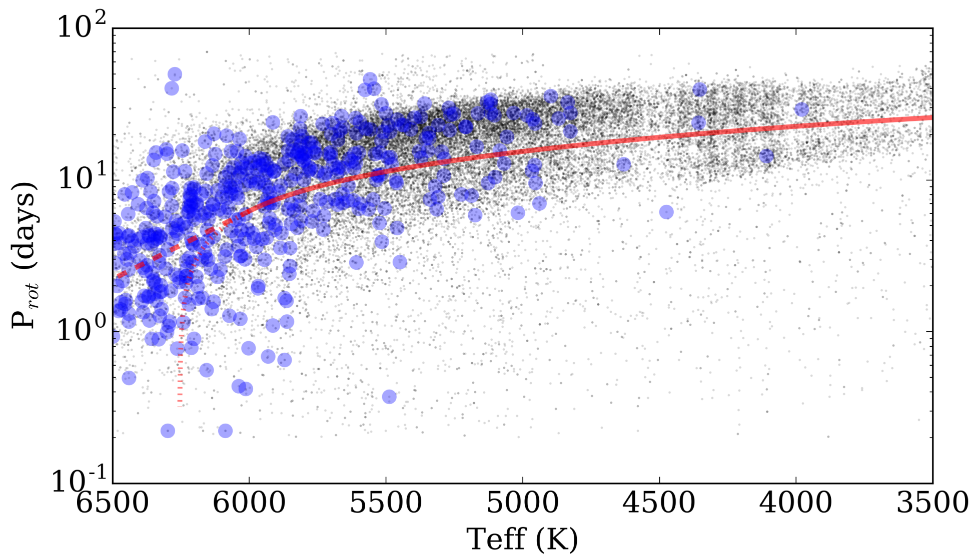

Figure 4. Rotation period versus temperature for TGAS-matched stars near the isochrone main sequence (blue circles). As in Figure 1, the full *Kepler*–Gaia matched sample is shown for reference (small black dots). The bimodality in rotation periods previously seen by McQuillan et al. (2014) extends the full range of temperatures in the *Kepler*–Gaia main sequence sample shown here. A Meibom et al. (2011) 600 Myr gyrochonology-isochrone roughly traces the bimodality midpoint up to 6000 K (red solid line), but deviates sharply up to ~6200 K (red dotted line). A log-linear extrapolation to of the isochrone from 6000K to 6500 K (red dashed line) continues to track the bimodality to hotter temperatures, and roughly traces a line of constant Rossby number.

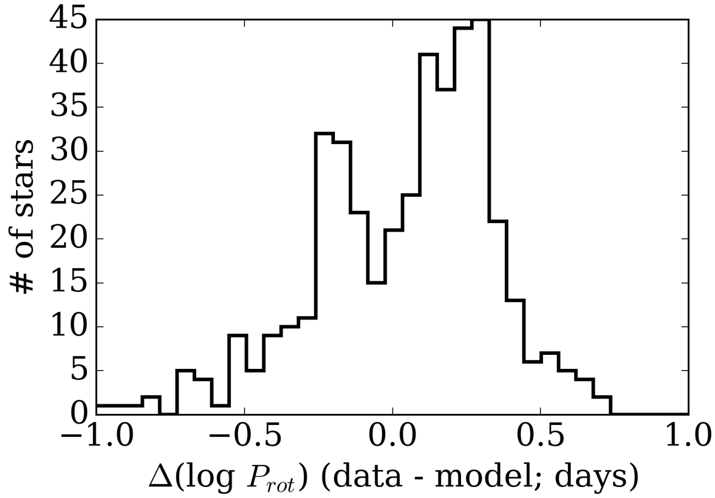

Figure 5. Residual of log rotation periods about the Meibom et al. (2011) 600 Myr isochrone, using the log-linear extrapolation between 6000–6500 K shown in Figure 4. The bimodal rotation period distribution is clear, with peaks at $\Delta \log P_{rot}$ -0.19 and 0.21 days.

us, which explains why it has not been seen in other gyro studies to date (e.g. clusters) Unfortunately not enough rotation period data across the fully convective boundary (∼3000 K) to tell if this bimodal feature continues.

the bimodality may be another manifestation of the "Vaughan Preston gap" (Vaughan & Preston 1980), e.g. discussed for rotating stars byKado-Fong et al. (2016). either due to fast evolution through intermediate stellar activity, or could be an age gap. if age, these clumps line up roughly with a 300 Myr and 2 Gyr Meibom et al. (2011) gyro-isochrone from cooler than about 6000 K. this similar to the non-continusous star formation history for the local solar neighborhood using Hipparcos astrometry (Hernandez et al. 2000). this age explanation was bolstered in McQuillan et al. (2013), who noted the two populations of rotating M dwarfs had different distributions of proper motions, indicating they belonged to distinct groups of stars. The distribution of total proper motion for stars above and below the modified 600 Myr gyrochrone is shown in Figure 6. Stars above the gyrochrone (slower rotators, nominally older) have a median total proper motion of 15.4 mas/yr, while those below (faster rotators, younger) have a median of 11.3 mas/yr. This difference in kinematics versus rotation period is in the same direction observed by McQuillan et al. (2013). As the typical error in the total proper motion is ∼1.4 mas/yr for this sample, this is a marginal (2.8σ) difference. Note also that likely contamination of subgiants in the hotter stars may also obscure kinematic differences.

finally, have shown utility for using Gaia data, combined with detailed light curve statitiscs from *Kepler*, to reveal hidden structure in properties of field stars. This combination will be super useful for determining approximate log g values (separating main sequence from sub-giants), and thus more accurate gyrochronology ages (van

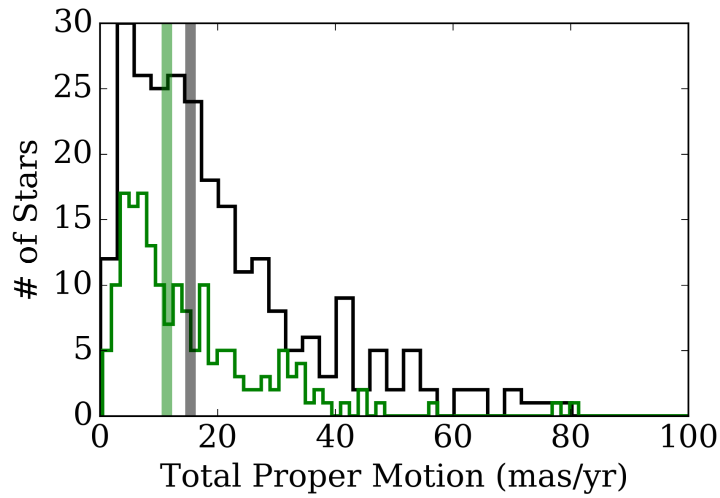

Figure 6. Total proper motion distributions for stars above (rotating slower, older stars) the gyrochrone model shown in Figure 4 (black) and below (rotating faster, younger stars) the model (green). Median values of the two distributions are shown (thick lines), which yield a marginal 2.8σ difference.

Saders & Pinsonneault 2013). also for modeling the star formation history of the entire milky way (e.g. Bertelli et al. 1999).

Special thanks to Jennifer van Saders, Sean Matt, and Travis Metcalfe for their helpful discussions that motivated publishing this work.

JRAD is supported by an NSF Astronomy and Astrophysics Postdoctoral Fellowship under award AST-1501418.

This research made use of the cross-match service provided by CDS, Strasbourg.

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

Bertelli, G., Bressan, A., Chiosi, C., & Vallenari, A. 1999, Baltic Astronomy, 8, 271

Borucki, W. J., Koch, D., Basri, G., et al. 2010, Science, 327, 977

Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127

Carrasco, J. M., Catalán, S., Jordi, C., et al. 2014, A&A, 565, A11

Creevey, O. L., Thévenin, F., Basu, S., et al. 2013, MNRAS, 431, 2419

Gaensicke, B., Tremblay, P.-E., Barstow, M., et al. 2015, ArXiv e-prints, arXiv:1506.02653

Gaia Collaboration. 2016, ArXiv e-prints, arXiv:1609.04153

Hernandez, X., Valls-Gabaud, D., & Gilmore, G. 2000, MNRAS, 316, 605

Kado-Fong, E., Williams, P. K. G., Mann, A. W., et al. 2016, ArXiv e-prints, arXiv:1608.00978

Lindegren, L., Lammers, U., Bastian, U., et al. 2016, ArXiv e-prints, arXiv:1609.04303

Lurie, J. C., Davenport, J. R. A., Hawley, S. L., et al. 2015, ApJ, 800, 95

McQuillan, A., Aigrain, S., & Mazeh, T. 2013, MNRAS, 432, 1203

McQuillan, A., Mazeh, T., & Aigrain, S. 2014, ApJS, 211, 24

Meibom, S., Barnes, S. A., Latham, D. W., et al. 2011, ApJL, 733, L9

Reinhold, T., Reiners, A., & Basri, G. 2013, A&A, 560, A4

Skumanich, A. 1972, ApJ, 171, 565

Stassun, K. G., & Torres, G. 2016, ArXiv e-prints, arXiv:1609.05390
van Saders, J. L., Ceillier, T., Metcalfe, T. S., et al. 2016, Nature, 529, 181
van Saders, J. L., & Pinsonneault, M. H. 2013, ApJ, 776, 67
Vaughan, A. H., & Preston, G. W. 1980, PASP, 92, 385