Draft version May 10, 2018
Typeset using LaTeX **preprint2** style in AASTeX62

Rotating Stars from *Kepler* Observed with Gaia DR2

James. R. A. Davenport[1, 2, *] and Kevin R. Covey[1]

[1]*Department of Physics & Astronomy, Western Washington University, 516 High St., Bellingham, WA 98225, USA*
[2]*Department of Astronomy, University of Washington, Seattle, WA 98195, USA*

ABSTRACT

We have matched the astrometric data from *Gaia* Data Release 2 to the sample of stars with measured rotation periods from *Kepler*. Using 30,305 stars with good distance estimates, we select 16,248 as being likely main sequence single stars within a 0.5 mag region about a 1 Gyr isochrone. This removes sub-giants and unresolved binary stars from the sample. The rotation period bimodality, originally discovered by McQuillan et al. (2013), is recovered for stars out to 525pc, but is not detectable at further distances. We also find a significant width in the stellar main sequence of M_G ~0.25 mag, as well as a increase in the average rotation period correlated with the M_G offset at a given color (mass). We interpret this to be the measurable change in luminosity and loss of angular momentum as stars evolve along the main sequence, which may provide a new independent test of stellar evolution and gyrochronlogy models. This investigation represents the first step in understanding the star formation history of our solar neighborhood as traced through stellar angular momentum loss.

1. INTRODUCTION

The *Kepler* mission (Borucki et al. 2010) a new era for enabling detailed study of angular momentum loss in low-mass stars. long noted as a means to possibly age-date stars (gyro), open clusters give hope that this general model works for low-mass stars many Qs exist about details. these include Qs about initial rotation period distribution (e.g. Barnes 2010; Matt et al. 2015), the specific prescription for spin-down (Angus et al. 2015), and exploring the efficiency of this angular momentum loss mechanism at old ages (van Saders et al. 2016).

Corresponding author: James. R. A. Davenport
James.Davenport@wwu.edu

* NSF Astronomy and Astrophysics Postdoctoral Fellow DIRAC Fellow

one of the most compelling results from the rotation work in *Kepler* is the discovery of a period bimodality. McQuillan et al. (2013) found bimodal feature, in M and later K stars (McQuillan et al. 2014). Davenport used Gaia DR1 to remove contamination from sub-giants and found the feature in G dwarfs. this feature proposed to be either a new short-lived transition or instability phase of momentum loss, or a signature of star formation history imprinted in the present-day rotation period distribution. However, to date this feature has only been observed in the *Kepler* rotation period catalog, and most critically only for stars within ~300 pc.

In this letter we follow the work of Davenport (2017) in studying the *Kepler* rotation period sample using astrometric data from the *Gaia* mission (Gaia Collaboration et al. 2016). By matching the McQuillan et al. (2014) rotation period catalog to the newest data from *Gaia* Data Release 2 (Gaia Collaboration et al. 2018), we can use precise distances for essentially every star to select likely main sequence dwarfs to distances well over 1 kpc. Importantly this filters out both sub-giants (the main contaminant noted by Davenport (2017)), and unresolved binary stars. Here we demonstrate the power of such a combined time-domain and astrometric sample for constraining the detailed evolution of main sequence stars themselves, and exploring the star formation history of the Milky Way.

2. THE *Kepler*–GAIA DATA

Our data xmatched by M. Bedell between *Kepler* and Gaia DR2 (CITE). using 1arcsec radius, which included 195,830 sources with stellar properties from the *Kepler* Data Release 25 and *Gaia* DR2.

sub-set was matched to the rotation catalog of McQuillan et al. (2014)

To select stars with good parallaxes, as well as high quality photometry from *Gaia*, we selected stars with the following criteria:

- Parallax error < 0.1 mas
- $\sigma(M_G)/M_G < 0.01$
- $\sigma(G_{BP})/G_{BP} < 0.01$
- $\sigma(G_{RP})/G_{RP} < 0.01$

distances using the updated prescription from Bailer-Jones et al. (2018) Following the suggested use of Bailer-Jones et al. (2018), we use only sources with `modality_flag` == 1 (i.e. not a bimodal distance solution) and `result_flag` == 1 (i.e. well constrained distance).

Our final sample contained 30,305 stars in Gaia DR2 with measured *Kepler* rotation periods that passed these selection criteria. A color–magnitude diagram of this sample is presented in Figure 1, with points colored by their rotation periods.

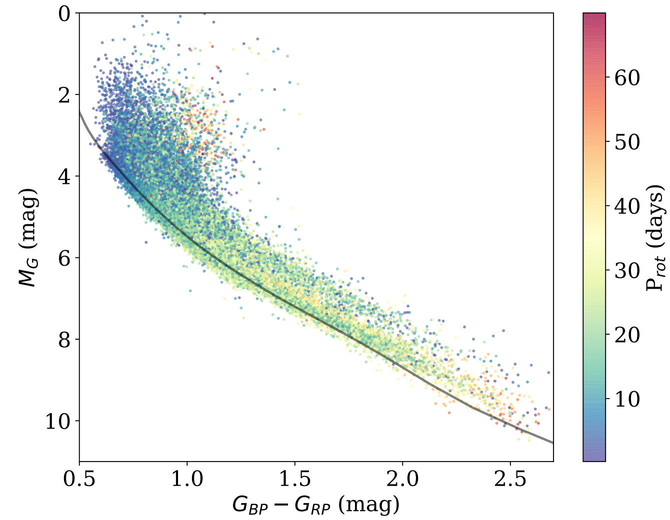

Figure 1. Color–magnitude diagram for 30,305 *Kepler* stars from the McQuillan et al. (2014) sample that are included in Gaia DR2, colored by their measured rotation period. For reference we show a 10^9 year MIST isochrone (black line) used to select likely main sequence, single stars (black line). A track of binary stars is apparent ∼0.75 mag above the main sequence. As in Davenport (2017), we find significant contamination of the rotation period sample for bluer stars by sub-giants.

3. SELECTING MAIN SEQUENCE STARS

As in Davenport (2017), the color–magnitude diagram shown in Figure 1 shows many of the bluer stars in the McQuillan et al. (2014) sample are significantly above the main sequence. These are likely subgiant stars, which do not follow the main sequence stars spin-down evolution (e.g. do Nascimento et al. 2012; van Saders & Pinsonneault 2013). Since Davenport (2017) found subgiants could obscure the rotation period bimodality for G dwarfs, these must be excluded from our analysis, but encourage future studies to explore the wealth of angular momentum evolution data from these most-main sequence objects.

Beyond the subgiant contamination above the main sequence, we can also see a secondary population of stars in a parallel track above the normal main sequence, which are likely unresolved binary stars. The pile-up above the main sequence occurs due to unresolved equal-mass field binaries, which was seen in the *Gaia* DR1 data as well (Anderson et al. 2017). Since these systems may have experienced tidal evolution that could significantly impact their rotation evolution (e.g. Lurie et al. 2017), we must also remove these from our analysis. Though we do not explore the binary population in any detail here, this sample (perhaps with radial velocity follow-up) may provide useful insight into the tidal evolution of binary stars.

we use the Mesa Isochrones and Stellar Tracks (MIST; Choi et al. 2016) to describe the main sequence stars in Figure 1 using [Fe/H] =0.25, and an age of 10^9 years. main seq stars chosen in 0.5 mag window

4. DISCUSSION

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

This work made use of the gaia-kepler.fun crossmatch database, created by Megan Bedell.

This project was developed as part of the 2018 NYC Gaia Sprint, hosted by the Center for Computational Astrophysics at the Simons Foundation in New York City.

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

REFERENCES

Anderson, L., Hogg, D. W., Leistedt, B., Price-Whelan, A. M., & Bovy, J. 2017, ArXiv e-prints, arXiv:1706.05055

Angus, R., Aigrain, S., Foreman-Mackey, D., & McQuillan, A. 2015, MNRAS, 450, 1787

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Mantelet, G., & Andrae, R. 2018, ArXiv e-prints, arXiv:1804.10121

Barnes, S. A. 2010, ApJ, 722, 222

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

Choi, J., Dotter, A., Conroy, C., et al. 2016, ApJ, 823, 102

Davenport, J. R. A. 2017, ApJ, 835, 16

do Nascimento, J.-D., da Costa, J. S., & Castro, M. 2012, A&A, 548, L1

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, ArXiv e-prints, arXiv:1804.09365

Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1

Lurie, J. C., Vyhmeister, K., Hawley, S. L., et al. 2017, AJ, 154, 250

Matt, S. P., Brun, A. S., Baraffe, I., Bouvier, J., & Chabrier, G. 2015, ApJL, 799, L23

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

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

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

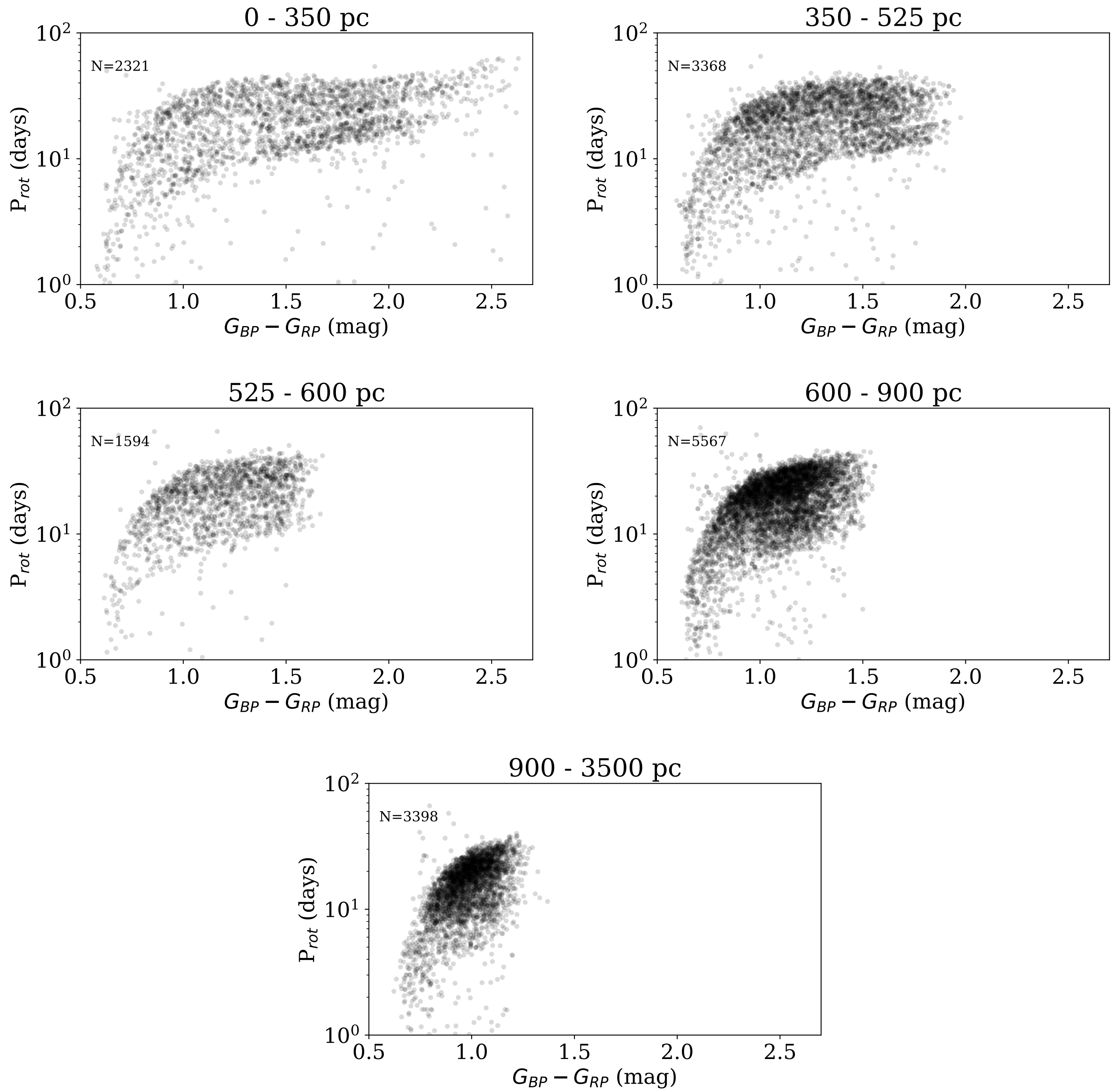

Figure 2. Color–period diagrams for our sample of likely main sequence stars, divided into bins of distance. Our nearest bin (within 350pc) is effectively the distance analyzed in Davenport (2017) using Gaia DR1, and clearly shows the rotation period bimodality for the entire sample. The brighter magnitude limit of the *Kepler* sample results in redder (fainter) stars missing in our further distance bins. The rotation period bimodality can be seen in the 350-525 pc bin, but is not found in the bluer stars at further distances.

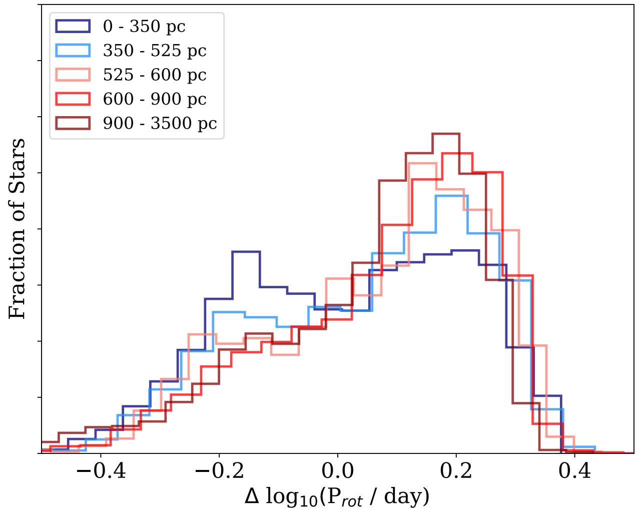

Figure 3. Histograms of the log rotation periods after a 600 Myr gyrochrone was subtracted for stars in the same five distance bins shown in Figure 2. The period bimodality for stars within 350 pc has two peaks similar to those found in Davenport (2017), at -0.15 and +0.18 dex. The fast rotating peak (left side) declines sharply at further distances, however.

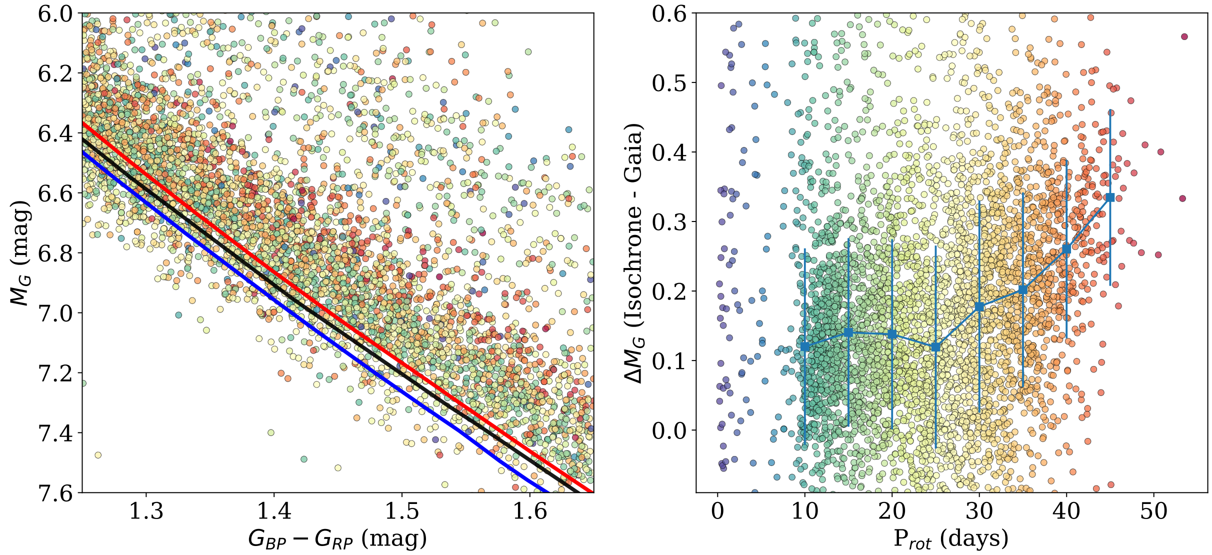

Figure 4. Left: Enlarged portion of the color–magnitude diagram from Figure 1 in a region centered near $\sim$0.75 M$_\odot$, with MIST isochrones at ages of 10^8, 10^9, and 10^10 yr for comparison (blue, black, and red lines). Points are colored by their measured *Kepler* rotation periods from McQuillan et al. (2014). The main sequence shows significant scatter, as well as a gradient in rotation period. Right: Difference in M_G from the 10^9 yr MIST isochrone, shown as a function of their rotation periods (point color again indicates rotation period). Blue squares show an increase in the median M_G offset in bins of increasing rotation period. Error bars shown are the standard deviation of ΔM_G in each bin.