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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 1,303 bright stars were recovered from the subset of Gaia sources with good astrometric solutions, most with temperatures hotter than 5000 K.

1. INTRODUCTION

Kepler mission (Borucki et al. 2010) has enabled statistical study of rotation periods for field stars for the first time. This fundamental stellar property has been measured for over 30k stars by tracing the periodic or quasi-periodic modulations of their light curves 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. 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, two period distributions found for M dwarfs in McQuillan et al. (2013), confirmed in up to K dwarfs McQuillan et al. (2014). Why this feature is not found at hotter temperatures, or has not been seen in other comprehensive rotation period studies (such as in open clusters), is a mystery. Currently favored explanations are an age distribution (CITE) or a rapid evolution through this period, similar to the Vaughan-Preston gap (?). Binary stars and period contamination by evolved stars may also be confounding our understanding of the period distribution seen for *Kepler* targets.

astrometric data from the Gaia mission (Gaia Collaboration 2016) can help shed light on this mystery. By measuring distances via stellar parallax, the *Kepler*–Gaia sample can separate single main sequence dwarfs from binary stars or evolved stars such as sub-giants, and can help calibrate fundamental properties of *Kepler* stars, such as log(g) (Creevey et al. 2013). This will help isolate the cause of the period bimodality,

In this paper I demonstrate the utility of combining *Kepler* rotation period sample with the preliminary Data Release 1 from Gaia (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. 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 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.

using CDS X-Match service, I matched the catalogs from these two surveys. The rotation period distribution is shown in Figure 1. A total of 41,739 *Kepler* rotation period sources were found in the Gaia DR1 catalog. A subset of 1,303 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 astrometry for nearly all *Kepler* stars.

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

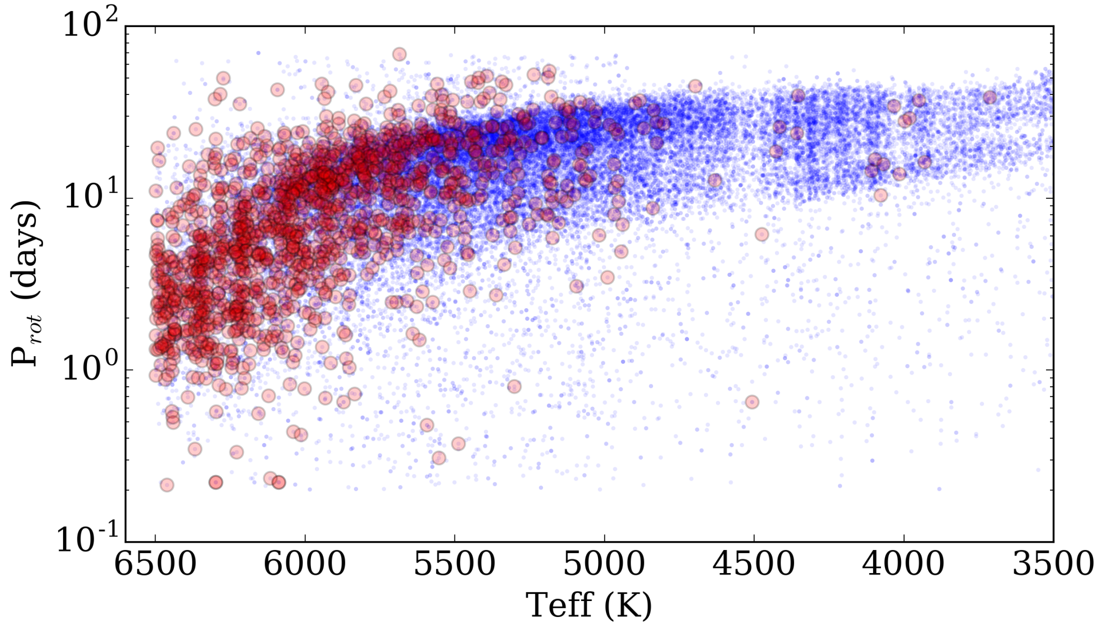

Figure 1. Rotation period distribution for 41,739 *Kepler* stars from McQuillan et al. (2014) with detections in Gaia DR1 (blue dots). The period bimodality can be seen most clearly for stars with $T_{eff} < 4000$ K as a dearth of sources with periods of $\sim$20 days, but extends to at least $T_{eff} \sim 5500$ K according to McQuillan et al. (2014). The subsample of 1,303 nearby objects found in TGAS are highlighted (red circles), and are mostly hotter stars due to the faint limit of the TGAS sample.

median distance of K/M stars ($T_{eff} > 4000$ K) is $\sim$216 pc, using isochrone median distance for the TGAS-matched sample (blue points) is very close, 285 pc, so also sampling just the most local volume. this points to the effect being localized around us, which explains why it has not been seen in other gyro studies to date (e.g. clusters) Unfortunately not enough rotation period data across the fully convective boundary ($\sim$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).

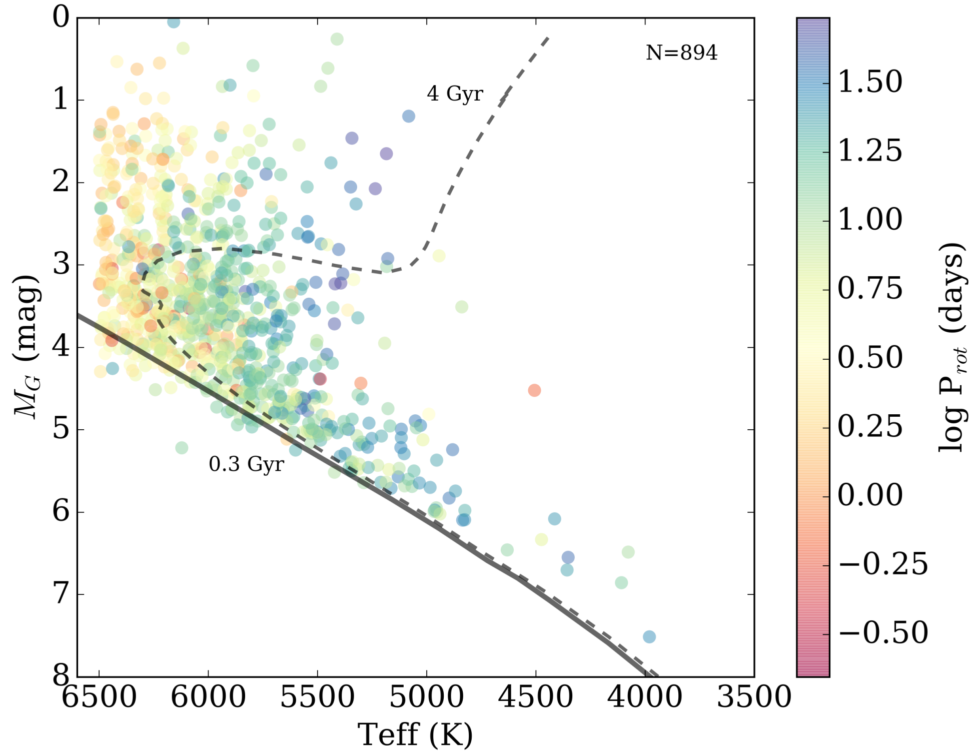

Figure 2. Hertzsprung–Russell (HR) diagram using temperatures from McQuillan et al. (2014) and Gaia DR1 G-band absolute magnitudes for the 894 stars that pass photometric and parallax quality cuts described in the text. Points are colored by their measured *Kepler* rotation periods. Two isochrones from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

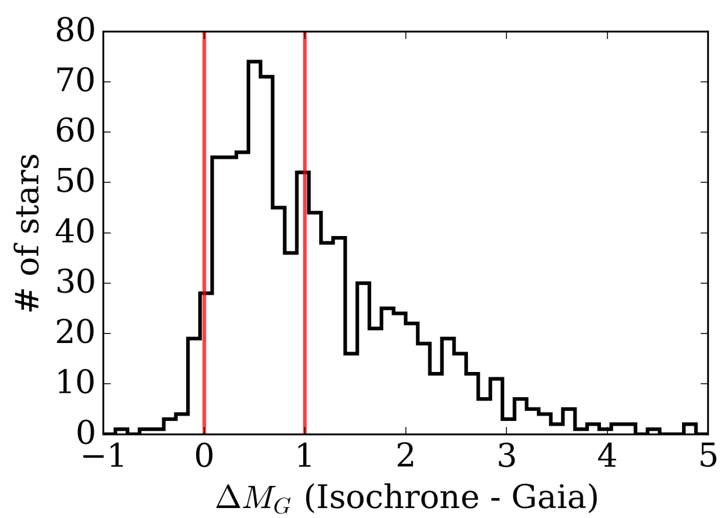

Figure 3. Distribution of differences between the Gaia DR1 G absolute magnitudes and values for main sequence stars from the 300 Myr isochrone shown in Figure 2. The range of sources selected near the single star main sequence (red lines) may have additional contamination due to dust extinction and binary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

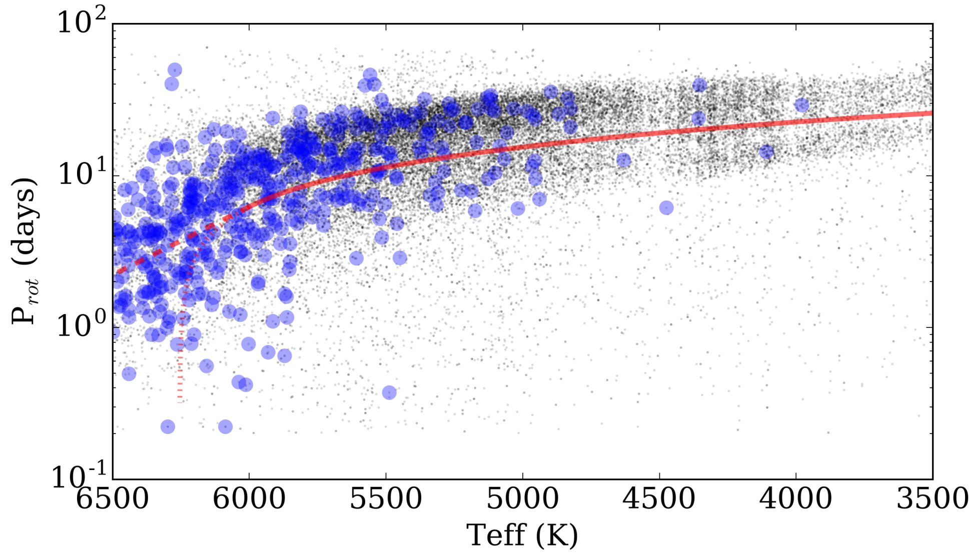

Figure 4. Rotation period versus temperature for TGAS-matched stars near the isochrone main sequence (blue circles). As in Figure 1, the full *Kepler*–Gaia matched sample is shown for reference (small black dots). The bimodality in rotation periods previously seen by McQuillan et al. (2014) extends the 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.

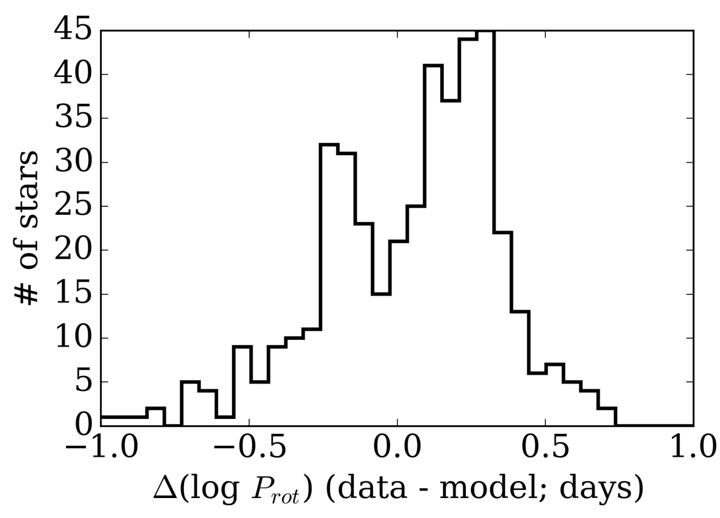

Figure 5. Residual of log rotation periods about the Meibom et al. (2011) 600 Myr isochrone, using the log-linear extrapolation between 6000–6500 K shown in Figure 4.

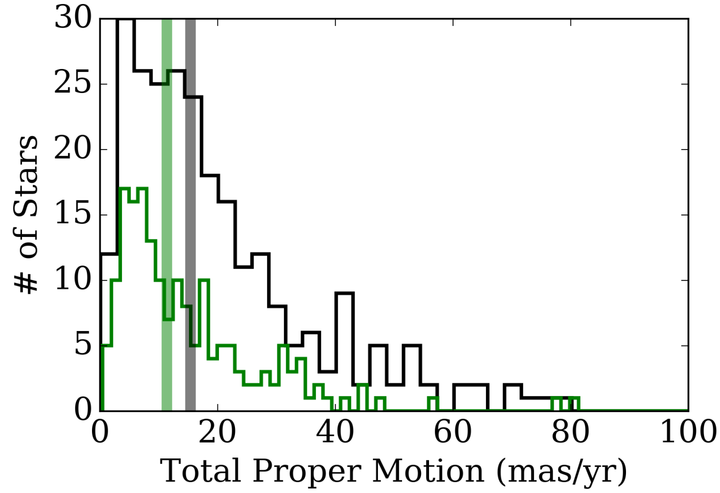

Figure 6. Total proper motion distributions for stars above (rotating slower, older stars) the gyrochrone model shown in Figure 4 (black) and below (rotating faster, younger stars) the model (green). Median values of the two distributions are shown (thick lines), which yield a marginal 2.8σ difference.

As the typical error in the total proper motion is $\sim$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 Saders & Pinsonneault 2013). also for modeling the star formation history of the entire milky way (e.g. Bertelli et al. 1999).

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