Exploring the origin of the rotation period gap using kinematics

Ruth Angus, *et al.*

ABSTRACT

The distribution of rotation periods of K and M stars, measured from light curves obtained from the *Kepler* spacecraft, has a sharp mass-dependent gap at around 10-20 days. This gap traces a line of constant age and constant Rossby number in the rotation period-effective temperature plane and its discovery has disrupted our understanding of stellar evolution. The origin of this gap is unknown, but possible physical explanations include a discontinuity in the local star formation history, or a discontinuity in the magnetic braking evolution of stars. An alternative explanation for the rotation period gap is measurement error caused by confounders such as binary companions or aliasing. For example, the lower rotation sequence could be a reflection of the upper sequence, caused by incorrect measurements at half the true period. In this paper, we rule out the possibility that this gap could be caused by incorrect period measurements or binary companions, by showing that the rapidly rotating stars are kinematically young and velocity dispersion increases smoothly with rotation period and gyrochronal age.

1. Introduction

[1]American Museum of Natural History, Central Park West, Manhattan, NY, USA

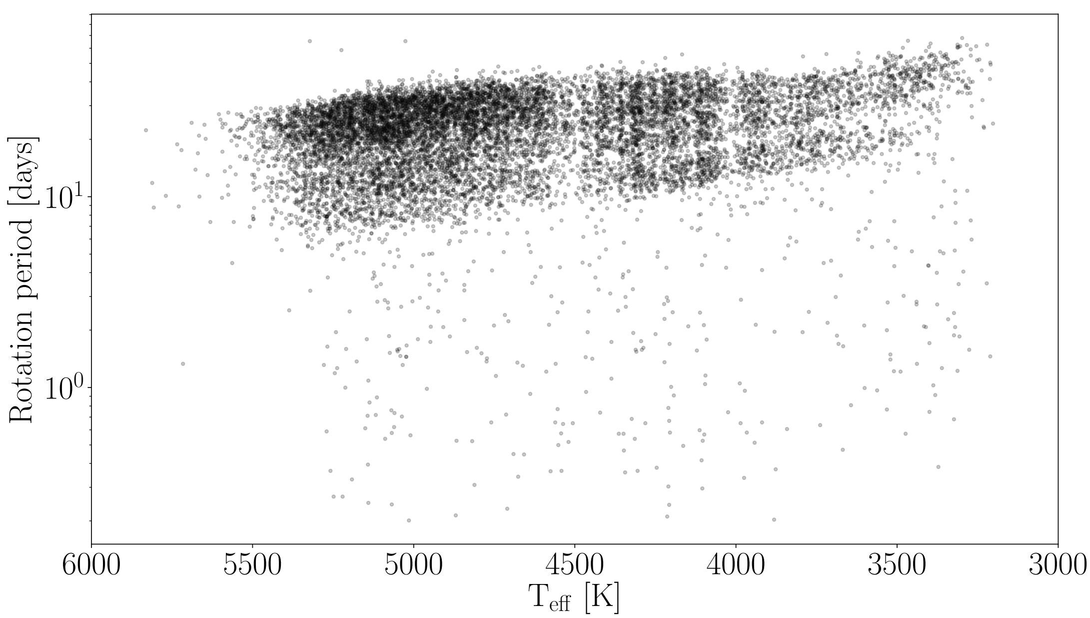
1.1. The rotation periods of cool main-sequence stars

The McQuillan et al. (2014) catalog was the first large-scale stellar rotation period catalog, generated from analyzing light curves from the *Kepler* spacecraft and remains one of the most valuable community products in the field of stellar astronomy. It contains around 34,000 rotation periods of FGKM dwarfs and subgiants, measured from autocorrelation functions (ACFs) of light curves. This catalog revealed a gap in the rotation periods of K and M dwarfs: a strip in the rotation vs effective temperature plane that is under-populated compared to the surrounding parts of parameter space. This gap can be seen in figure 1. The rotation period gap is most prevalent for low-mass stars, of spectral type K and M, but was recently shown to extend through G, F and A types as well (**?**).

Three explanations for the origin of this gap have been proposed. Firstly, since the gap falls on what is thought to be an isochrone in period-effective temperature space, it follows that it may be caused by a discontinuity in the age distribution of the sample. The gap could be created if there exist two populations of stars with different age distributions, with the distribution of young ages peaking at around 800 Myr, and the distribution of old ages peaking at around 2-3 billion years. This idea was investigated by McQuillan et al. (2014), who suggested that the two populations might be the thin and thick disk of the Milky Way. However, they found no sharp change in kinematic properties between the two samples. In addition, the thin/thick disk transition is thought to be around 6-8 Gyr, which is older than the majority of stars in the McQuillan et al. (2014) sample (citations). A short pause in star formation is difficult to explain by invoking, *e.g.* the passage of a spiral arm through the Solar neighbourhood, since an increase in gas density would be expect to boost, not quench, star formation rate. However perhaps the Solar neighbourhood passed between two spiral arms around 1 billion years ago, however pattern speed, orbital period (200 Myrs)... seems unlikely. Possible passage of a dwarf galaxy but, again, this would be expected to boost star formation, not suppress it.

The second explanation for the rotation period gap is that stars either transition rapidly across the gap, *i.e.* experience a rapid phase of angular momentum loss at an age of around 1 billion years, or become magnetically inactive for a short period of time such that their rotation periods become undetectable. This first scenario could be caused by a sudden recoupling between the core and envelope, where core and envelope rotate differentially before the gap, then angular momentum is radially redistributed and stars rotate as solid bodies after the gap. The latter scenario is hinted at by **?** who noticed that the amplitudes of light curves decrease smoothly either side of the gap, as though stars gradually become more inactive until they have no large-scale surface features and their rotation periods become almost impossible to detect. **?** suggest that a transition between a spot-dominated and

Fig. 1.— The rotation periods of 18,259 FGKM dwarf stars, measured by McQuillan et al. (2014), vs. their effective temperatures. We applied cuts to the *Gaia* color-magnitude diagram of these stars (figure 2) in order to remove equal-mass binaries and subgiants from the sample. The rotation period gap can be seen as an almost-horizontal gap toward the right of this figure.



faculae-dominated regime could lead to a cancelling-out of surface features.

The final explanation for the rotation period gap is one of measurement error or confounding by binarity.

As of May 2019, the McQuillan et al. (2014) catalog has been used more than 250 times, for a range of studies spanning fields from exoplanets to white dwarfs, to galactic archaeology. Since it underpins so many astronomical studies, a large number of incorrectly measured rotation periods in this catalog would undermine several of the studies built upon it.

1.2. Using kinematics to solve the mystery

Stars are thought to be born in the thin disk of the Milky Way, orbiting the center of the galaxy with a low out-of-plane, or vertical, velocity (W, or v_z). Young stars have relatively small vertical velocities, but gain momentum in the vertical direction over time. Although the cause of orbital heating is not well understood, interactions with giant molecular clouds and spiral arms are thought to play an important role (citations). Although the velocity of any individual star will only provide a weak age constraint, the velocity dispersion of a group of stars can indicate whether, on average, that group is old or young relative to other groups. In this work we compare the velocity dispersions of groups of stars to ascertain which groups are older and which younger and draw conclusions based on the implied relative ages of populations. Since the age-velocity dispersion relations (AVRs) are themselves still actively being calibrated, it is difficult to directly compare gyrochronal ages with kinematic ones. However, regardless of the exact relation between velocity dispersion and stellar age, it is expected to be a monotonic relationship, therefore velocity dispersion can be used effectively to *rank* groups of stars by age.

Vertical action is a better age indicator than vertical velocity, however both vertical action (J_z) and vertical velocity ($v_\mathbf{z}$/W) can only be calculated with full 6-dimensional position and velocity information. Unfortunately, most stars with measured rotation periods do not have radial velocity (RV) measurements because they are relatively faint *Kepler* targets ($\sim$11th-18th magnitudes). For this reason, we used an alternative age proxy: velocity in the direction of galactic latitude, $v_\mathbf{b}$. The *Kepler* field is positioned at low galactic latitude (b=5-20°), so $v_\mathbf{b}$ is a close approximation to $v_\mathbf{z}$.

2. Method

2.1. The data

We crossmatched the McQuillan et al. (2014) catalog of stellar rotation periods, measured from *Kepler* light curves, with the *Gaia* DR2 catalog. Reddening and extinction from dust was calculated for each star using the Bayestar dust map implemented in the dustmaps *Python* package (?). We estimated effective temperatures from dereddened *Gaia* $G_{BP} - G_{RP}$ color, using an 8th-order polynomial relation calibrated using .... stars ask Jason for details.

$$\mathrm{T_{eff}} = 8960 - 4802C + 1931C^2 - 2446C^3 + 2669C^4 - 1324C^5 + 301C^6 - 26C^7, \quad (1)$$

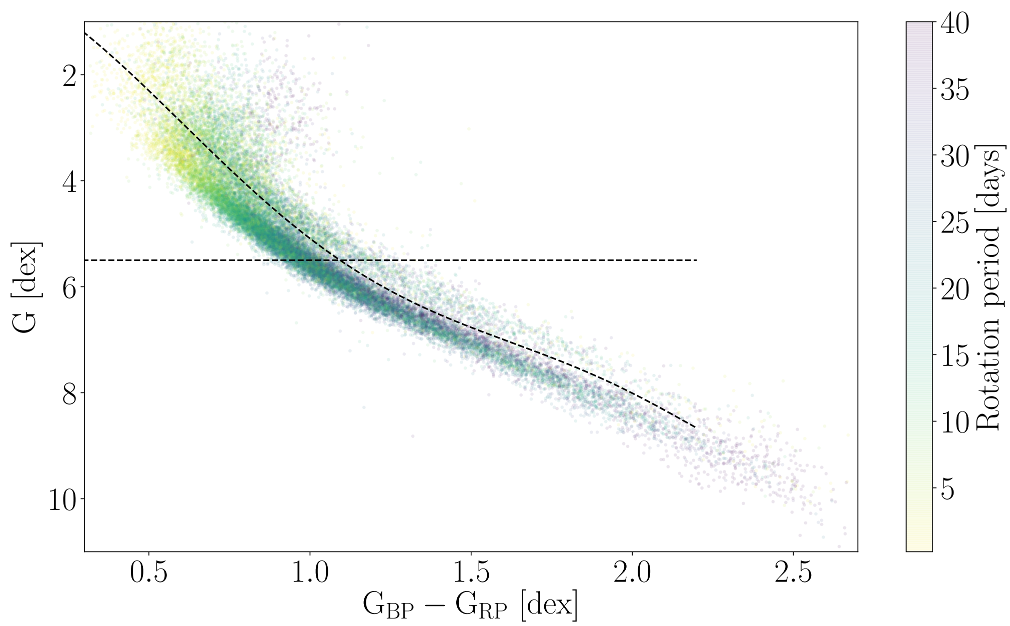
where C is *Gaia* $G_{BP} - G_{RP}$.

We removed visual binaries and subgiants from the sample as the rotation-period evolution of these two types of stars is generally different to that of single stars which more usually follow a Skumanich-like spin-down law. We removed visual binaries and subgiants from the sample by applying cuts to the color-magnitude diagram (CMD), shown in figure 2. We fit a 6th-order polynomial to the main sequence and raised it by 0.22 dex, to approximate the division between single stars and visual binaries. We eliminated visual binaries by removing all stars above this line from the sample, and subgiants by removing stars brighter than 6th magnitude in *Gaia* G-band.

We removed stars with negative parallaxes and parallax signal-to-noise ratios below 10 and a small number of stars fainter than 16th magnitude from the sample. We used the `Pyia` (?) and `astropy` (??) *Python* packages to calculate stellar velocities. `Pyia` has built-in functionality for calculating velocity samples from the full *Gaia* uncertainty covariance matrix via Monte Carlo sampling. It therefore not only incorporates uncertainties on the *Gaia* positions parallaxes and proper motions, it also accounts for the *covariance* between these properties. Finally, we removed stars with absolute $v_{\mathbf{b}}$ uncertainties greater than 1 kms^{-1} from the sample.

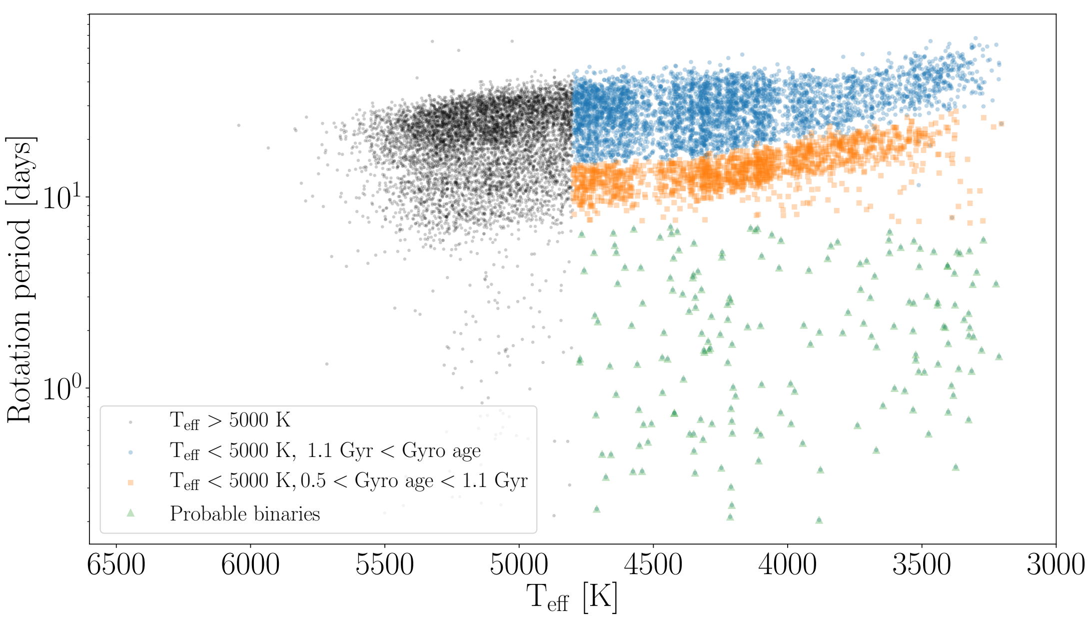
Gyrochronal ages were calculated using a polynomial gyrochronology relation calibrated to Praesepe and the Sun (?). We used dereddened *Gaia* $G_{BP} - G_{RP}$ color to calculate these ages. Figure 3 shows the McQuillan et al. (2014) rotation period sample, separated into three groups: stars above the gap in blue (classified as stars older than 1.1 Gyr), stars below the gap in orange (younger than 1.1 Gyr but older than 0.5 Gyr), and stars that are likely to be synchronized binaries (younger than 0.5 Gyr). We used a gyrochronal isochrone (often called a gyrochrone) to separate these groups of stars because the rotation period gap appears to fall on a gyrochrone of 1.1 Gyr, and because the lower envelope of rotation periods is also shaped like a gyrochrone at 0.5 Gyr. This is probably because there is not a significant

Fig. 2.— A *Gaia* color magnitude diagram showing the McQuillan et al. (2014) sample with extinction-corrected magnitudes, colored by rotation period. We excluded photometric binaries and subgiants from our analysis by removing stars above the two dashed lines. The rotation periods of binaries and subgiants do not follow a Skumanich-like braking law. The rotation period gradient across the main sequence is visible by eye in this figure: young, rapidly rotating stars are located below the old, slowly rotating stars.



number of stars younger than 500 Myr in the *Kepler* field. Stars with short rotation periods, that seem younger than 500 Myr according to the **?** gyrochronology relation are likely to be binaries. Stars rotating more rapidly than 7 days were shown to be mostly synchronized binaries (**?**). This is also borne out in the results section of this paper. Although most rapid rotators are likely synchronized binaries (and therefore not actually young – just rotating rapidly because of tidal synchronization), *some* of the rapid rotators probably *are* young and this could be an extremely interesting group of stars from a scientific standpoint.

Fig. 3.— The rotation periods of stars in the McQuillan et al. (2014) sample vs. effective temperature, with visual binaries and subgiants removed. Blue circle points are non-photometric binary dwarfs, cooler than 4800 k, with a rotation period and *Gaia* color indicating they are older than 1.1 gyr. orange squares are stars that with rotation periods that fall just below the gap: they have rotation-ages between 0.5 and 1.1 gyrs. Green triangles are stars with rotation periods faster than the main envelope of stars. These are probably binaries whose rotation periods are synchronized to their orbits and have been spun-up via tidal interactions.



3. Results

- Velocity dispersion smoothly increases

4. Discussion

5. Conclusion

REFERENCES

Ruth Angus *et al.* Towards precise stellar ages: combining isochrone fitting with empirical gyrochronology. *AJ*, in prep.

Astropy Collaboration, T. P. Robitaille, E. J. Tollerud, P. Greenfield, M. Droettboom, E. Bray, T. Aldcroft, M. Davis, A. Ginsburg, A. M. Price-Whelan, W. E. Kerzendorf, A. Conley, N. Crighton, K. Barbary, D. Muna, H. Ferguson, F. Grollier, M. M. Parikh, P. H. Nair, H. M. Unther, C. Deil, J. Woillez, S. Conseil, R. Kramer, J. E. H. Turner, L. Singer, R. Fox, B. A. Weaver, V. Zabalza, Z. I. Edwards, K. Azalee Bostroem, D. J. Burke, A. R. Casey, S. M. Crawford, N. Dencheva, J. Ely, T. Jenness, K. Labrie, P. L. Lim, F. Pierfederici, A. Pontzen, A. Ptak, B. Refsdal, M. Servillat, and O. Streicher. Astropy: A community Python package for astronomy. *A&A*, 558:A33, October 2013. doi: 10.1051/0004-6361/201322068.

Gregory M. Green. dustmaps: A Python interface for maps of interstellar dust. *The Journal of Open Source Software*, 3(26):695, Jun 2018. doi: 10.21105/joss.00695.

A. McQuillan, T. Mazeh, and S. Aigrain. Rotation Periods of 34,030 Kepler Main-sequence Stars: The Full Autocorrelation Sample. *ApJS*, 211:24, April 2014. doi: 10.1088/0067-0049/211/2/24.

A. M. Price-Whelan, B. M. Sipőcz, H. M. Günther, P. L. Lim, S. M. Crawford, S. Conseil, D. L. Shupe, M. W. Craig, N. Dencheva, A. Ginsburg, J. T. VanderPlas, L. D. Bradley, D. Pérez-Suárez, M. de Val-Borro, (Primary Paper Contributors, T. L. Aldcroft, K. L. Cruz, T. P. Robitaille, E. J. Tollerud, (Astropy Coordination Committee, C. Ardelean, T. Babej, Y. P. Bach, M. Bachetti, A. V. Bakanov, S. P. Bamford, G. Barentsen, P. Barmby, A. Baumbach, K. L. Berry, F. Biscani, M. Boquien, K. A. Bostroem, L. G. Bouma, G. B. Brammer, E. M. Bray, H. Breytenbach, H. Buddelmeijer, D. J. Burke, G. Calderone, J. L. Cano Rodríguez, M. Cara, J. V. M. Cardoso, S. Cheedella, Y. Copin, L. Corrales, D. Crichton, D. D'Avella, C. Deil, É. Depagne, J. P. Dietrich, A. Donath, M. Droettboom, N. Earl, T. Erben, S. Fabbro, L. A. Ferreira, T. Finethy,

R. T. Fox, L. H. Garrison, S. L. J. Gibbons, D. A. Goldstein, R. Gommers, J. P. Greco, P. Greenfield, A. M. Groener, F. Grollier, A. Hagen, P. Hirst, D. Homeier, A. J. Horton, G. Hosseinzadeh, L. Hu, J. S. Hunkeler, Ž. Ivezić, A. Jain, T. Jenness, G. Kanarek, S. Kendrew, N. S. Kern, W. E. Kerzendorf, A. Khvalko, J. King, D. Kirkby, A. M. Kulkarni, A. Kumar, A. Lee, D. Lenz, S. P. Littlefair, Z. Ma, D. M. Macleod, M. Mastropietro, C. McCully, S. Montagnac, B. M. Morris, M. Mueller, S. J. Mumford, D. Muna, N. A. Murphy, S. Nelson, G. H. Nguyen, J. P. Ninan, M. Nöthe, S. Ogaz, S. Oh, J. K. Parejko, N. Parley, S. Pascual, R. Patil, A. A. Patil, A. L. Plunkett, J. X. Prochaska, T. Rastogi, V. Reddy Janga, J. Sabater, P. Sakurikar, M. Seifert, L. E. Sherbert, H. Sherwood-Taylor, A. Y. Shih, J. Sick, M. T. Silbiger, S. Singanamalla, L. P. Singer, P. H. Sladen, K. A. Sooley, S. Sornarajah, O. Streicher, P. Teuben, S. W. Thomas, G. R. Tremblay, J. E. H. Turner, V. Terrón, M. H. van Kerkwijk, A. de la Vega, L. L. Watkins, B. A. Weaver, J. B. Whitmore, J. Woillez, V. Zabalza, and (Astropy Contributors. The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package. *AJ*, 156:123, September 2018. doi: 10.3847/1538-3881/aabc4f.

Adrian Price-Whelan. adrn/pyia: v0.2. Apr 2018. doi: 10.5281/zenodo.1228136.

This preprint was prepared with the AAS LaTeX macros v5.0.