

New asteroseismic rotation rates of *Kepler* dwarfs show strong agreement with weakened magnetic braking on the late-age main sequence

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Studies using asteroseismic ages and rotation rates from star spot rotation have shown that standard age-rotation relations break down roughly half-way through the main sequence lifetime, a phenomenon referred to as weakened magnetic braking. While rotation rates from spots can be difficult to determine for older, less active stars, rotational splitting of asteroseismic oscillation frequencies can provide rotation rates for both active and quiescent stars.

We obtained asteroseismic rotation rates of 91 main sequence stars showing high signal-to-noise modes of oscillation. Using these new rotation rates, along with effective temperatures, metallicities and seismic masses and ages, we built a hierarchical Bayesian mixture model to determine whether the ensemble more closely agreed with a standard rotational evolution scenario [1], or one where weakened magnetic braking takes place [2]. The weakened magnetic braking scenario was found to be 98.4% more likely for our stellar ensemble, adding to the growing body of evidence for this stage of stellar rotational evolution. This work represents the largest catalogue of seismic rotation on the main sequence to date, opening up possibilities for more detailed ensemble analysis of rotational evolution with *Kepler*.

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1 Introduction

Gyrochronology is the study of the relationship between a star’s rotation period and its age. As a star grows older along the main sequence, magnetic winds will cause it to lose angular momentum, slowing it down. Because the loss rate is related to temperature, the rotation period of a young star will rapidly settle on to a plane in age-colour-rotation space [3]. As a result, knowing the rotation and colour of a star provides an avenue to measure it’s age, which can otherwise be difficult to come by, enabling more in-depth studies of stellar populations [4, 5].

Gyrochronology was previously calibrated on stellar clusters, which have well constrained ages, but only up to roughly 2.5 Gyr so far [6]. With the launch of the *Kepler* mission [7], ages of main sequence field stars (i.e. not in clusters) became more widely available through asteroseismology, the study of stellar variability [8]. When looking at these stars disagreements were found with gyrochronology beyond the middle of their main sequence lifetime, which could not be reconciled with existing theories [9, 10, 11]. It was proposed that at some stage in a star’s evolution it undergoes *weakened magnetic braking* (WMB, [2]), where the efficiency of angular momentum loss rapidly drops, causing stars to keep fast rotation rates that we were not expected in existing gyrochronology relations.

The mechanism by which weakened magnetic braking occurs is still subject to debate, and may be connected to changes in the magnetic field morphology [12, 13, 14, 15]. It may also be explained from an observational point of view. A large scale survey of stellar rotation rates measured using star spots pointed out a lack of slowly rotating stars older than Sun [16]. As activity reduces with age, older stars with fewer star spots are less likely to have their rotation measured [17]. The point at which the detection probability drops appears to lie at a similar level of activity to that at which the proposed weakened magnetic braking takes place, pitting these two possibilities against one another [18].

Determining whether weakened magnetic braking is a true phenomenon or a bias in star spot observations requires new data, which can be provided by asteroseismology. A star’s rotation causes modes of oscillation to split into multiplets, making it possible to measure the rate of rotation by measuring oscillation frequencies [19]. Asteroseismic rotation is more difficult to obtain than rotation from star spots, but does not require spots to be visible, meaning that we can measure rotation for quiescent stars that would not have been present in existing catalogues of star-spot rotation. Previous studies have shown that asteroseismic rotation rates probe the near-surface of the star, making them comparable to spot rotation rates, and the perfect avenue to explore whether weakened magnetic braking truly takes place [20, 21]. Here, we measured asteroseismic rotation rates of 91 main sequence stars across a broad range of colours and ages, and evaluate this new ensemble to determine whether it agrees more closely with a classical rotational evolution scenario, or one where weakened magnetic braking takes place.

2 Data

In order to obtain robust asteroseismic rotation rates, we required detections of multiples of both dipole (denoted as $\ell = 1$) and quadrupole ($\ell = 2$) oscillations for each star, of which

the latter have significantly lower signal-to noise. Radial oscillations ($\ell = 0$), which are also visible, do not split. In this work, we studied a sample of 94 of the highest signal-to-noise targets observed by *Kepler*, combining the ‘Kages’ [8, 22] and LEGACY [23, 24] catalogues*.

For the purposes of studying gyrochronology, we wanted to be able to single out stars for which the loss of angular momentum via magnetized winds is the dominant source of rotational evolution. Stars with $T_{\text{eff}} > 6250$ K fall beyond the ‘Kraft’ break, which roughly separate stars with large convective envelopes (at lower temperatures) from those with thin ones (high temperatures), at which the efficiency of angular momentum transport is greatly reduced. We also wanted to single out stars that have started to evolve onto the sub-giant branch, where the outer envelope begins to expand, making them challenging targets for gyrochronology. While there are no identified mixed dipole modes[†] in the stars in our sample, indicating an evolved structure, we can still apply a conservative sub-giant classification of stars with $\log(g) < 4.0$ dex. [26].

Our sample spans surface gravities of $3.8 \text{ dex} < \log(g) < 4.6 \text{ dex}$ and temperatures of $5000 \text{ K} < T_{\text{eff}} < 6700 \text{ K}$. Of our full sample of 95 targets, 67 stars fall in the range $\log(g) > 4.0 \text{ dex}$, $T_{\text{eff}} < 6250 \text{ K}$, which we call main sequence (MS) stars. Four targets in our sample have $\log(g) < 4.0 \text{ dex}$, $T_{\text{eff}} < 6250 \text{ K}$ which we class as potentially being sub-giants (SG stars). The remaining 24 stars in our sample have $T_{\text{eff}} > 6250 \text{ K}$, which we class as being hot main sequence stars.

Neither catalogues reported stellar rotation, so we repeated the mode frequency fitting with a model that accounted for this in more detail (see *Methods*).

3 Results

4 Discussion

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*For these catalogues the mode extraction through frequency fitting [22, 23] and modelling using mode frequencies to obtain stellar parameters [8, 24] are covered in separate papers.

[†]In evolved stars, gravity modes propagating in the radiative interior will interfere with non-radial p modes, changing their structure and creating so-called ‘mixed modes’ [25].

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Acknowledgements

Methods

Author Contributions