Weakened magnetic braking as the origin of anomalously rapid rotation in old field stars

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A knowledge of stellar ages is crucial for our understanding of many astrophysical phenomena, and yet ages can be difficult to determine. As they become older, stars lose mass and angular momentum, resulting in an observed slowdown in surface rotation1. The technique of ‘gyrochronology’ uses the rotation period of a star to calculate its age2,3. However, stars of known age must be used for calibration, and, until recently, the approach was untested for old stars (older than 1 gigayear, Gyr). Rotation periods are now known for stars in an open cluster of intermediate age4 (NGC 6819; 2.5 Gyr old), and for old field stars whose ages have been determined with asteroseismology5,6. The data for the cluster agree with previous period–age relations1, but these relations fail to describe the asteroseismic sample7. Here we report stellar evolutionary modelling5,6,8–10, and confirm the presence of unexpectedly rapid rotation in stars that are more evolved than the Sun. We demonstrate that models that incorporate dramatically weakened magnetic braking for old stars can—unlike existing models—reproduce both the asteroseismic and the cluster data. Our findings might suggest a fundamental change in the nature of ageing stellar dynamos, with the Sun being close to the critical transition to much weaker magnetized winds. This weakened braking limits the diagnostic power of gyrochronology for those stars that are more than halfway through their main-sequence lifetimes.

There are two approaches to the calibration and testing of gyrochronology. The first is a purely empirical approach, which uses a sample of stars with independently measured ages and rotation periods to construct period–age relationships. These relationships are generally simple power laws that take into account age, period, and some mass–dependent quantity; they have seen wide usage1,2,4,5,7. The second, model-based approach uses stellar models and a prescription for magnetic braking to account for the functional dependence of the rotation period on all relevant stellar quantities, but relies on calibrators to determine the magnitude of the angular momentum loss. For this reason, the model-based approach is well suited for calibrating samples that cover parameter space only sparsely; it also provides a method for attaching physical meaning to observed braking behaviour.

Magnetic-braking prescriptions are typically scaled from the solar case; for example, the Skumanich relation1 yields angular momentum loss of the form \(\frac{dJ}{dt} \propto \omega^3\), where \(t\) is time, \(J\) is angular momentum, and \(\omega\) is the angular rotation velocity11. These relations often use the dimensionless Rossby number—defined as the ratio of the rotation period to the convective overturn timescale, \(\text{Ro} = \frac{P}{\tau_{\text{conv}}}\)—to characterize departures from this simple power law. Rossby-number thresholds and scalings are routinely invoked to parameterize the magnetic-field strength12,13; the dependence of the spin-down on stellar mass and composition14; the observed saturation of magnetic braking in rapid rotators; and the sharp transition from slow to rapid rotation that occurs in hot stars (of greater than 6,250 K) because of their thinning convective envelopes15. Under traditional prescriptions, stars undergo braking throughout their main-sequence lifetimes, regardless of rotation rate. Observations of stellar clusters of young and intermediate ages have indicated that such treatments are reasonable16,17. However, there is a dearth of old stars with which to test such relationships, owing to the long-period, low-amplitude signatures of rotation in such stars, and to the challenge of age measurements in field stars. Data from the Kepler telescope provide a first test of these prescriptions in stars that are older than the Sun.

The high-precision, long-baseline light curves from Kepler make such investigations possible. The rotation of a star manifests itself in Kepler data as a periodic modulation in the intensity, as dark starspots rotate into and out of view. Intensity variations due to stellar oscillations are likewise present in the light curve, on shorter timescales. Low-degree modes of oscillation probe the conditions of the deep stellar interior and internal structure of the star, providing ages that are precise to better than 10% in stars for which many oscillation modes are detected at high signal-to-noise ratios16.

The first efforts to calibrate the gyrochronology relations using Kepler seismic targets uncovered tension between the cluster and seismic samples8. Although the form of the mass–period–age relation used in this study9 was similar to those in previous studies12,13, the range of ages and more sophisticated treatment of observational uncertainties made it possible to determine that the sample did not obey a single power-law period–age relation. However, even this approach has limitations: it does not account for metallicity or for changes in the stellar moment of inertia, and it relied on a sample for which detailed seismic modelling and spectroscopic data were lacking for some stars, biasing the seismic ages.

To address the limitations of previous work and to take full advantage of precisely determined stellar parameters, we utilize a subset of 21 Kepler stars—selected to have detailed asteroseismic modelling and high-precision ages, measured rotation periods, and measured metallicities5,6,8–10—and couple these observations to stellar evolutionary models. Sample selection, details of the modelling to derive asteroseismic ages, and extraction of rotation periods are described in the Methods. Figure 1 shows the surface—in terms of period, age and effective temperature (\(T_{\text{eff}}\), a proxy for mass)—upon which the stars are expected to lie12,14. Actual cluster and seismic data are overplotted; while the clusters and young asteroseismic targets lie close to the plane, the intermediate-age and old asteroseismic stars are strikingly discrepant and nearly all lie below the surface, owing to the fact that they are rotating more rapidly than expected. When we account...
Figure 1 | The period–age plane as predicted by gyrochronology, compared with observed periods. The empirical gyrochronology relation\textsuperscript{2,4} is shown as a plane. Data from open stellar clusters are shown as small squares (NGC 6811 cluster; 1 Gyr) and triangles (NGC 6819 cluster; 2.5 Gyr). Large circles represent the seismic sample of 21 stars that are detected in the Kepler data; this sample falls systematically below the plane. The solar symbol (⊙) marks the Sun, which falls on the plane by design. The effective temperature, $T_{\text{eff}}$, is a proxy for mass.

We therefore conclude that magnetic braking is weaker in these intermediate-age and old stars. We extend our model by postulating that, in addition to the Rossby scaling already present in the theoretical models\textsuperscript{14}, effective loss of angular momentum ceases above a critical Rossby threshold\textsuperscript{12}. We modify the prescription for angular momentum loss\textsuperscript{14} to conserve angular momentum above a specified $R_{\text{crit}}$. Graphs showing the effects of varying $R_{\text{crit}}$ values on the models are provided in Fig. 3. The inclusion of the threshold has the desired effect: it reproduces the existing gyrochronology relations and cluster data at young ages, when Ro is smaller because of more rapid rotation, but allows stars to maintain unusually rapid rotation periods at late times. Furthermore, it reproduces the trend in mass that is apparent in Figs 2 and 3 (and the trend in the zero-age main-sequence (ZAMS) $T_{\text{eff}}$ which selects stars with similar rotational histories; we perform all fits using the seismic mass, but use ZAMS $T_{\text{eff}}$ for display to simplify the figures). Hotter, more massive stars reach the critical Rossby threshold at younger ages, and we therefore see discrepancies between the fiducial gyrochronology relationships and the observations at earlier times as ZAMS $T_{\text{eff}}$ increases. The best-fit value for the Rossby threshold, given our sample, is $R_{\text{crit}} = 2.16 \pm 0.09$ ($\chi^2 = 13.3$) for the modified models. The shaded grey regions in Figs 2 and 3 denote the full range of period ratios ($P_{\text{period}}/P_{\text{predicted}}$) and the period–age combinations allowed for a model with $R_{\text{crit}} = 2.16$, given the ranges of ZAMS $T_{\text{eff}}$ that are represented in each panel. These regions encompass all combinations of mass (0.4–2.0 solar masses) and metallicity ($-0.4 < [Z/H] < +0.4$) that together produce a star within the appropriate ZAMS $T_{\text{eff}}$ range for each panel of Figs 2 and 3, on both the main-sequence and the subgiant branch.

We emphasize that our result—that old stars are rotating anomalously rapidly—persists regardless of the choice of period–age

Figure 2 | Ratios of the predicted rotation period\textsuperscript{14} to the observed period. Predicted rotation periods are derived from existing period–age relations; observed periods are as detected by the Kepler telescope. These ratios are plotted against stellar age. Stars are divided according to decreasing ZAMS $T_{\text{eff}}$: a, 5,900–6,200 K; b, 5,600–5,900 K; c, 5,100–5,400 K. Period ratios for open clusters are shown as black symbols, as follows: diamonds, M37; circles, Praesepe; squares, NGC 6811; triangles, NGC 6819. The Sun (⊙) is also marked. Coloured circles represent seismic targets; coloured triangles represent known planet hosts; coloured squares represent the binary stars 16 Cygni A and B. All errors are shown to 1σ. Stars are coloured according to ZAMS $T_{\text{eff}}$ with blue representing the hottest stars and red the coolest stars. Shaded regions represent the period ratios permitted in each $T_{\text{eff}}$ bin for a model in which $R_{\text{crit}} = 2.16$.
fit in the old stars until \( \alpha \) is greater than \(~20\), suggesting that the braking is indeed drastically reduced. However, we do observe spot modulation in these stars, which implies at least small-scale magnetic activity. The starspot properties may or may not directly reflect changes in the large-scale magnetic field that governs spin-down. A change in field geometry from a simple dipole to higher-order fields could produce weakened braking\(^{18,19}\), as could a change in the distribution of spots on the stellar surface\(^{20}\). It could also be the case that the large-scale field strength undergoes a transition at high Rossby numbers\(^12\). Abrupt changes in the efficiency of angular momentum loss have been proposed in order to explain the rotational distributions in young clusters\(^{31}\), and there is evidence for a Rossby-number-governed shift in field morphologies in low-mass M dwarfs\(^{32}\). Observations of detailed magnetic-field morphologies and corresponding simulations are lacking for stars at higher Rossby numbers than the Sun, and both are critical to understanding the source of the observed anomalous rotation.

Regardless of the mechanism that governs the spin-down, the observation that existing rotation–age relationships do not predict the observed rotation rates has immediate implications for gyrochronology. The rotation periods of the middle-aged stars that have passed this Rossby threshold represent only lower limits on the age. The empirical calibrations must be modified, and the weakened relationship between period and age will result in substantially more uncertain rotation-based ages for stars in the latter halves of their lives. The presence of such a Rossby threshold defines boundaries in mass–age space, past which gyrochronology is incapable of delivering precise ages.

**Online Content** Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to J.L.v.S. (jvansaders@obs.carnegiescience.edu) or R.A.G. (rafael.garcia@cea.fr) for computers code.
METHODS

Sample selection. Our sample can be divided into two principal target types: Kepler Asteroseismic Science Consortium (KASC) targets, and Kepler Objects of Interest (KOIs). We focus on those stars with (modelled) ZAMS $T_{\text{eff}}$ values (defined as the point at which hydrogen fusion dominates the stellar luminosity) below 6,200 K, where magnetic braking should be most important. We show the positions of the selected stars on a Hertzsprung–Russell diagram in extended Data Fig. 1, and period–age plot in Extended Data Fig. 2.

As described elsewhere, the asteroseismic age is drawn from a magnitude-limited sample of 2,000 Sun-like stars that were selected for a one-month period of short-cadence (~1-minute) Kepler observations on the basis of their properties in the Kepler Input Catalog (KIC). Of these stars, roughly 500 displayed evidence of solar-like oscillations. A subset of targets with detections of oscillations that show high signal to noise ratio detections of oscillations were selected for continued monitoring over Kepler quarters 5–17. Of this sample, the noise frequencies for a subset of 61 high-signal-to-noise stars were extracted; there are high-resolution spectroscopic data for 46 of these. We modelled 42 of these 46 stars with the asteroseismic modelling portal (AMP; described below), excluding 4 targets whose spectra contained a complicated pattern of mixed modes. Of the 42 modelled targets, 11 were both detected in spot modulation and classified as ‘simple’ solar-like oscillators that did not show the seismic hallmarks of F-stars and evolved subgiants. A further three (non-overlapping) targets were added.$^7$ Of this sample of 14, 12 targets have AMP ZAMS $T_{\text{eff}}$ values of less than 6,200 K, yielding a total of 12 stars in the KASC sample.

The KOI sample$^8$ was selected from the 77 KOIs observed in short cadence that displayed signatures of solar-like oscillations. Of these, 35 power spectra were of sufficient quality to extract individual mode frequencies to be modelled, 33 of which represent unevolved main-sequence stars. A subset of 11 have periods detected via spot modulation$^6$, 7 of which have an AMP ZAMS $T_{\text{eff}}$ of less than 6,200 K.

Finally, we add the two well studied stars from the 16 Cygni binary to our sample; for these stars, asteroseismic ages$^{16}$ and rotation periods have been inferred from asteroseismic mode splittings.$^{23}$ In total, 21 stars are addressed in this analysis. Where available, we use the updated asteroseismic frequencies of ref. 24. Extended Data Table 1 shows the seismic (mass, age) and spectroscopic ($T_{\text{eff}}, [\text{Fe/H}]$) values and rotation periods for these stars.

Age and period measurements. Asteroseismic ages are determined using two methodologies: AMP, which provides the ages used in most of this paper; and the Bayesian stellar algorithm (BASTA) pipeline, used to verify that the discrepancies in predicted and observed rotation periods are not the result of pipeline choice. AMP uses a genetic algorithm to perform a search for the global optimal stellar properties, but BASTA also uses the individual frequencies by drawing a 21-star sample with replacement from the original data 50,000 times, then recalculating the best-fit $\text{Ro}_{\text{crit}}$ for each realization. Cluster data and the Sun are not used in this fit. An alternate fit allowing parameters important for late-time braking to vary ($f_{\text{ke}}$, $\text{Ro}_{\text{crit}}$) and including intermediate-age and older rotation data from the seismic sample, NGC 6819, and the Sun (52 stars in total) yields a best-fit $\text{Ro}_{\text{crit}}$ of 2.1 ± 0.1, with $f_{\text{ke}} = 8.4 ± 0.2$.

Predicted model periods are obtained by using the mass and age from the asteroseismic pipelines coupled with the spectroscopic metallicities.$^{8,10,11}$ Model uncertainties are estimated by generating 50,000 (20,000 for $\text{Ro}_{\text{crit}}$, $f_{\text{ke}}$ fit) realizations of the input parameters (M, $T_{\text{eff}}$, [Fe/H]), where values are drawn from a Gaussian distribution centred on the observed value, with 1σ errors defined by the observational uncertainties. We search in the fundamental space of mass, age, and composition, we select only models which fall within 5σ of the observed $T_{\text{eff}}$. This constraint has little or no effect for unevolved stars, but ensures that stars at the turnoff (KIC 6196457 and KIC 8349582 in particular) are not assigned artificially long rotation periods due to mass–age combinations that fall on the subgiant branch. $1\sigma$ uncertainties on the model periods are defined as the values that enclose 68% of the resulting models.

Empirical gyrochronology relations. We verify that the unexpectedly rapid rotation in old, solar-like stars is independent of the spin–down prescription by repeating our exercise with an empirical literature gyrochronology relation.$^2$ We replicate Fig. 2 in Extended Data Fig. 3 with predicted periods drawn from an empirical gyrochronology calibration, based on equation (32) in ref. 2: $t = \frac{\ln \left( \frac{P_{\text{obs}}}{P_{\text{crit}}} + \frac{k_{\text{lc}}}{2\pi} (P_{\text{obs}} - P_{\text{crit}}^2) \right)}{k_{\text{lc}}}$ where $t$ is the age, $\tau$ is the convective overturn timescale, $P$ is the period, and $P_{\text{crit}}$ is the initial period. We adopt values for $k_{\text{lc}}$ of 0.646 million years (Myr) per day and for $k_{\text{lc}}$ of 452 days per Myr; $P_{\text{crit}} = 11.1$ days, and the global $\tau - T_{\text{eff}}$ relation is as used in refs 2.4, 50.000 realizations of the combination ($T_{\text{eff}}, t$) are drawn from a Gaussian

or gravitational settling. We use the ‘fast launch’ conditions$^{14}$ for modelling the rotation, but have validated that our results are insensitive to the choice of initial conditions. Changing the launch conditions typically shifts the period ratio (in sense of expected/observed) by less than 50% of the quoted errors, and shifts the fitted critical Rosby number to $\text{Ro}_{\text{crit}} = 2.15 ± 0.08$. The model $\text{Ro}_{\text{crit}}$ is the local convective overturn timescale, defined as the ratio of the typical mixing length to the convective velocity at one pressure scale height above the base of the convective envelope in the mixing length theory of convection. Under this definition, the solar rotation period ($P_{\text{obs}}$) is 25.4 days, $\tau_{\text{crit}}$ = 1.015 × 10$^6$ s, and $P_{\text{crit}} = 2.16$.

The weakened magnetic braking is modelled by modifying the braking law such that a star with $P_{\text{obs}} > \text{Ro}_{\text{crit}}$ is evolved under the assumption of conservation of angular momentum, such that the rotation period depends only on the changing moment of inertia of the star as it evolves. The modified loss law is given by the following equations (based on equations (1) and (2) in ref. 14):

$$\frac{dJ}{dt} = f_{\text{k}} \frac{K \sigma}{\omega} \left( \frac{\omega}{\omega_{\text{crit}}} \right)^2, \quad \omega_{\text{crit}} \leq \omega_{\text{crit}} \leq \text{Ro}_{\text{crit}}$$

$$0, \quad \text{Ro}_{\text{crit}} > \omega_{\text{crit}}$$

where $f_{\text{k}}$ is a constant factor used to scale the loss law during the empirical fitting; $\omega_{\text{crit}}$ is the saturation threshold (important only at young ages); $\tau_{\text{crit}}$ is the convective overturn timescale; $P_{\text{phot}}$ is the pressure at the photosphere; $R$ is the radius; $M$ is the mass; $L$ is the luminosity; and $\odot$ refers to the Sun. The term $c(t)$ sets the centrifugal correction; because our stars are slowly rotating and the correction should be small, we set $c(t)$ to a constant value of 1. This braking law is fit to open–cluster data and the Sun, where the initial rotation period, disk-locking timescale, $\omega_{\text{crit}}$ and $f_{\text{k}}$ were allowed to vary, and all other parameters were determined using stellar evolutionary models.$^{15}$ When fitting for an optimal $\text{Ro}_{\text{crit}}$, we keep the parameters of the magnetic braking law calibrated on the Sun and open clusters fixed, and vary only the $\text{Ro}_{\text{crit}}$ at which braking is allowed to cease. $\text{Ro}_{\text{crit}}$ is optimized using a $\chi^2$ figure of merit (valid under the assumption of independent observations and Gaussian uncertainties): $\chi^2 = \sum_{i=1}^{n} (P_{\text{obs},i} - P_{\text{mod},i})^2 / (\sigma_{P_{\text{obs}},i}^2 + \sigma_{P_{\text{mod}},i}^2)$, where $\sigma_{P_{\text{obs}},i}$ is the observational uncertainty on the extracted period, and $\sigma_{P_{\text{mod}},i}$ represents the uncertainty on the model period given the uncertainties on the input masses, ages, and compositions. We derive uncertainties on $\text{Ro}_{\text{crit}}$ using bootstrap resampling, drawing a 21-star sample with replacement from the original data 50,000 times, and recalculating the best-fit $\text{Ro}_{\text{crit}}$ for each realization. Cluster data and the Sun are not used in this fit. An alternate fit allowing parameters important for late-time braking to vary ($f_{\text{ke}}$, $\text{Ro}_{\text{crit}}$) and including intermediate-age and older rotation data from the seismic sample, NGC 6819, and the Sun (52 stars in total) yields a best-fit $\text{Ro}_{\text{crit}}$ of 2.1 ± 0.1, with $f_{\text{ke}} = 8.4 ± 0.2$.

To model the magnetic braking law, the magnetic braking law is evolved under the assumption of conservation of angular momentum, such that the rotation period depends only on the changing moment of inertia of the star as it evolves. The modified loss law is given by the following equations (based on equations (1) and (2) in ref. 14):
distribution centred on the measured values, with a 1σ width defined by the quoted observational errors on the central values. These empirical relationships do not account for the physical expansion of stars as they evolve (particularly near the end of the main sequence) and therefore tend to predict somewhat more rapid rotation than do full theoretical models near the main sequence turnoff. Cluster data. To provide comparison with the typical gyrochronological calibrators, we draw cluster data from a variety of literature sources. For the cluster M37 we adopt the following cluster parameters: extinction, E(B−V) = 0.227 ± 0.038 mag; total metal abundance [M/H] = 0.045 ± 0.044 dex; age = 550 ± 30 Myr. Rotation data and cluster parameters are25 for Praesepe (M44) are included, with E(B−V) = 0.027 ± 0.004, [Fe/H] = 0.11 ± 0.03, and log(age) = 8.78 ± 0.01. For NGC 6811, we adopt the g′-colours, E(B−V) value of 0.1, and rotation periods as in ref. 26, as well as the [M/H] value of −0.1 ± 0.01 and age of 1.00 ± 0.05 Gyr from ref. 27. Finally, for NGC 6819 we use the rotation periods and B−V colours from ref. 4, with the age (2.5 ± 0.2 Gyr) and adopted metallicity (0.09 ± 0.03) from ref. 28. B−V colours are converted into temperatures and stellar masses using Yale rotating stellar evolution (YREC) isochrones24. We model cluster stars in the same manner as the seismic targets, with 10,000 mass−age−composition realizations for each star. We display the mean cluster rotation periods for all stars within the ZAMS Τeff bins, with errors representing the 16th and 84th percentiles. In M37 and Praesepe in particular, the rotational distribution displays a range resulting from spread in the initial rotation periods. Sample biases. We demonstrate that our results are unlikely to be a consequence of selection bias in our sample. The sample is subject to two sources of selection bias: asteroseismic detectability, and the detectability of spot modulation. Detailed asteroseismic analysis requires a high signal-to-noise detection of the power excess from oscillations. Oscillation amplitudes scale roughly as Amax ∝ (E/M) (Τeff)−2 (equation 7) from ref. 30, referring to l = 0 radial modes; seismic samples are therefore strongly biased towards more-massive stars. There is also a bias towards bright targets, where lower noise levels contribute to detectability. Our sample is drawn from two subsets of stars: the one-month survey stars from the seismic sample, and the KOIs. We expect the one-month survey seismic detections at magnitudes of Kp of less than ~10, while the roughly 1,000-day time series in short cadence collected for the KOI sample allow detections out to Kp ~ 12, which well describes the actual magnitude distribution of our sample (see Fig. 6 in ref. 30). The strong trends with magnitude and mass are well predicted by basic scaling arguments, save for the dependence on activity: active stars are less likely to be detected in oscillations46. Our sample is selected seismically, and we do not expect the well understood seismic biases to favour rapid rotators (apart from the obvious mass dependence).

Variability owing to starspots scales with the rotation period, in the sense that more rapid rotation is associated with higher amplitudes of variability15. One could imagine that we are detecting the rapidly rotating tail of a distribution of rotation periods, or detecting objects spun up by binary/potential interactions or mergers. This first case is at odds with what we know from open clusters: as late as 2.5 Gyr, there is a converged, well defined rotational sequence that shows very little scatter at fixed mass2. If we are in fact detecting a rapidly rotating subset of the population, the dispersion in rotation and spin-down rates must set in after several billion years, or it would be visible in the open-cluster data. If there is dispersion in the rotation periods, it represents a serious challenge to the validity of gyrochronology for old stars, regardless of its source. The pipeline used to extract the rotation periods for this work has been tested with an injection and recovery exercise17. Our recovery fraction is shown in Extended Data Fig. 4, and demonstrates that we should be able to detect stars that are substantially less active than the Sun at longer periods. However, this exercise does not account for stars that simply cease to have spots to detect on their surfaces; under this scenario, slow rotators could exist but be undetectable. We cannot directly combat this concern given our current data set, although we can examine the case of 16 Cygni (16 Cyg). 16 Cyg A and B are not detected in spot modulation; directly combat this concern given our current data set, although we can examine the case of 16 Cygni (16 Cyg). 16 Cyg A and B are not detected in spot modulation; under this scenario, slow rotators could exist but be undetectable. We cannot infer that these stars have solar-like activity, nor can we infer that these stars have solar-like activity, nor can we infer that the activity of Sun-like stars depends on the host star, in the KOI sample, and no known hot Jupiters. In the case of the seismic sample, there is no evidence for double-lined binaries, photometric–spectroscopic temperature disagreements, multiple oscillating components, or unusual dilution of the seismic power spectra, and no evidence of eclipses. Finally, if mergers (planetary or stellar) were responsible for all detections of rapid rotation, then the 50% detection rate of the ‘simple stars’7 in spot modulation implies an uncomfortably high merger rate. The asteroseismic age scale. We carry out two tests to demonstrate that the discrepancy between the expected and observed rotation periods is not due to a systematic bias in the ages with roots in the asteroseismic age scale. We show that ages derived with the BASTA pipeline display the same trend in rotation period, and that systematically shifting the asteroseismic ages, while improving the fit, is inferior to instituting a Rossby threshold. Extended Data Fig. 5 provides period ratio plots using the BASTA ages and BASTA Τeff determinations. The systematic trend in the period ratios survives. The Barnes relation7 fits with χ2 = 184.3, and the fiducial models14 with χ2 = 68.4. A fit for Τcrit using the BASTA ages yields Τcrit = 2.67 ± 0.50. Bootstrap resampling demonstrates that this number is sensitive to whether KIC 8349582 is drawn; if KIC 8349582 is excluded, the fit becomes Τcrit = 2.12 ± 0.12. We also investigate the possibility that the seismic age scale is systematically shifted relative to the true ages. We perform model fits with the fiducial braking law with an extra parameter that allows for a systematic age shift. For the AMP ages, χ2 is minimized with the Barnes relation with a systematic shift of 35% and a χ2 of 78.5. Likewise, the fiducial models14 prefer a shift of 20 ± 3% with a χ2 of 26.9. In both cases, the required systematic shifts are larger than the estimated 9.6% systematic uncertainties in seismic ages18. Finally, to verify that we are not biased by the fact that the ages and periods were determined using different evolution codes, we tune the physics in the fiducial models14 to match that of the AMP models, and predict the rotation periods for the central AMP values of the masses, ages, and compositions of each star. In particular, we match the diffusion physics, opacity tables, equation of state, helium and metal abundances, boundary conditions, and important nuclear reaction rates present in the ASTEC code used for AMP. The results are presented in Extended Data Fig. 6, and demonstrate that the discrepancy between the predicted and observed periods is preserved. We conclude that our result is not the consequence of assumptions about the stellar physics included in models. Code availability. The AMP science code used to infer stellar ages can be downloaded at https://amp.phys.au.dk/about/evolpack. Code for the period extraction and rotational evolution will be publicly released upon completion of the necessary documentation. YREC likewise has no public documentation, and has not been publicly released. BASTA is undergoing major revisions for increased speed and documentation. YREC likewise has no public documentation, and has not been publicly released. BASTA is undergoing major revisions for increased speed and is not yet publicly available.

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Extended Data Figure 1 | The positions of all 21 Kepler stars on the Hertzsprung–Russell diagram. We plot spectroscopic $T_{\text{eff}}$ (a proxy for mass) versus seismic log($g$) (surface gravity), with 1σ observational error bars; the symbol size is proportional to the period ratio (AMP ages, fiducial models\textsuperscript{14}). Colours and symbol conventions are as in Fig. 2. Evolutionary tracks are overplotted for $[Z/H] = +0.3$ (dotted lines) and $[Z/H] = -0.1$ (solid lines), for masses 0.8–1.3 $M_\odot$ in increments of 0.1 $M_\odot$. ($[Z/H] = +0.3, M = 0.8 M_\odot$ is beyond the plotted area.)
Extended Data Figure 2 | Period–age plot of sample stars. The 21-star sample, with observed rotational periods plotted against AMP asteroseismic ages. Symbol conventions are as in Fig. 2. The solid line denotes the empirical relation for $T_{\text{eff}} = 5,800$ K (approximately equal to the mean sample $T_{\text{eff}}$). All error bars represent $1\sigma$. 
Extended Data Figure 3 | Period ratios using empirical gyrochronology relations. Ratios of predicted periods to observed periods are plotted as a function of the AMP asteroseismic age, and divided according to AMP ZAMS $T_{\text{eff}}$ (a, ZAMS $T_{\text{eff}} = 5,900$–6,200 K; b, ZAMS $T_{\text{eff}} = 5,600$–5,900 K; c, ZAMS $T_{\text{eff}} = 5,100$–5,400 K.) Error bars represent 1σ. Symbol conventions are as in Fig. 2.
Extended Data Figure 4 | Detectability of stars in spot modulation. Detection fractions for the 750 stars with noise in the hound-and-hare exercise of ref. 17, as a function of activity level $A$ (where the activity level of the Sun is defined as $A_\odot = 1$) and rotation period. The total number of light curves searched for periodicity in each cell is overplotted. The dashed black line at $P = 35$ days represents the expected period for stars like the Sun under traditional gyrochronology relations found in the literature.
Extended Data Figure 5 | Predicted versus observed rotation periods using ages determined with BASTA. a, c, e. Plotted are the ratios of the periods predicted using the fiducial models\textsuperscript{14} to the observed rotation periods, as a function of stellar age. The grey band represents the offset expected from models in which $R_{\text{crit}} = 2.16$. All error bars represent 1$\sigma$. b, d, f. Ratios of the predicted periods obtained from the empirical relation\textsuperscript{2} to the observed periods, plotted against stellar age. Stars are divided according to ZAMS $T_{\text{eff}}$, using BASTA ZAMS $T_{\text{eff}}$ values: a, b, 5,900–6,200 K; c, d, 5,500–5,900 K; e, f, 5,100–5,400 K. All symbol conventions are as in Fig. 2.
Extended Data Figure 6 | The shift in the period ratios induced by changing the stellar model input physics. Circles are colour-coded according to ZAMS $T_{\text{eff}}$ as in Fig. 2. Ratios of the periodicity expected from the fiducial model$^{14}$ to the observed periodicity are plotted against age. Arrows denote the shift in the period ratio that occurs when YREC models$^{14}$ are run to match the AMP–ASTEC physics.
Extended Data Table 1 | Rotation periods, asteroseismic data and spectroscopic quantities for sample stars

| KIC  | AMP       | BASTA/GARSTEC | Spectroscopic |
|------|-----------|---------------|---------------|
|      | Mass      | Age           | log(g)        | ZAMS | Mass    | Age | ZAMS | T_{eff} [GW] | [Fe/H] | Period | Note     |
| 16Cyg A | 1.10±0.02 | 7.07±0.46    | 4.295 567    | 1.04±0.01  | 6.95±0.26 | 5668 | 5825±50 | +0.09±0.02  | 23.8±1.7  | 23.2±7.4 | seismic period |
| 16Cyg B | 1.06±0.02 | 6.82±0.28    | 4.360 5629   | 0.99±0.005 | 7.02±0.14 | 5592 | 5750±50 | +0.05±0.02  | 13.9±2.1  | 13.9±2.1 | seismic period |
| 3427720 | 1.13±0.04 | 2.23±0.17    | 4.388 5985   | 1.12±0.02  | 2.22±0.31 | 6019 | 6040±84 | -0.03±0.09  | 13.9±2.1  | 13.9±2.1 | seismic period |
| 3656476 | 1.17±0.03 | 8.13±0.59    | 4.248 5642   | 1.07±0.01  | 7.68±0.42 | 5525 | 5710±84 | +0.25±0.09  | 31.7±3.5  | 31.7±3.5 | seismic period |
| 5184732 | 1.27±0.04 | 4.17±0.40    | 4.270 5905   | 1.18±0.02  | 4.05±0.42 | 5810 | 5840±84 | +0.38±0.09  | 19.8±2.4  | 19.8±2.4 | seismic period |
| 6116048 | 1.01±0.03 | 6.23±0.37    | 4.270 5838   | 1.06±0.02  | 5.54±0.34 | 5943 | 5935±84 | -0.24±0.09  | 17.3±2.0  | 17.3±2.0 | seismic period |
| 6196457 | 1.23±0.04 | 5.51±0.71    | 4.053 6064   | 1.21±0.02  | 5.52±0.50 | 5991 | 5871±94 | +0.17±0.11  | 16.4±1.2  | 16.4±1.2 | KOI      |
| 6521045 | 1.04±0.02 | 6.24±0.37    | 4.118 5933   | 1.11±0.02  | 6.50±0.51 | 5886 | 5829±75 | +0.02±0.10  | 25.3±2.8  | 25.3±2.8 | KOI      |
| 7680114 | 1.13±0.03 | 7.19±0.70    | 4.184 5801   |  ---  ---   |  ---  --- |  ---  --- | 5855±84 | +0.11±0.09  | 26.3±1.9  | 26.3±1.9 | seismic period |
| 7971531 | 0.84±0.02 | 9.15±0.47    | 4.479 5253   | 0.84±0.02  | 10.10±0.99 | 5240 | 5400±84 | -0.24±0.09  | 33.7±2.6  | 33.7±2.6 | seismic period |
| 8006161 | 1.04±0.02 | 5.04±0.17    | 4.502 5165   | 0.94±0.005 | 5.08±0.10 | 5250 | 5390±84 | +0.34±0.09  | 29.8±3.1  | 29.8±3.1 | seismic period |
| 8349582 | 1.19±0.04 | 7.93±0.94    | 4.178 5695   | 1.07±0.02  | 8.03±0.75 | 5630 | 5699±74 | +0.30±0.10  | 51.0±1.5  | 51.0±1.5 | KOI      |
| 9098294 | 1.00±0.03 | 7.28±0.51    | 4.314 5718   | 1.01±0.02  | 6.93±0.57 | 5734 | 5840±84 | -0.13±0.09  | 19.8±1.3  | 19.8±1.3 | seismic period |
| 9139151 | 1.14±0.03 | 7.17±0.19    | 4.376 6092   | 1.16±0.02  | 1.79±0.46 | 6019 | 6125±84 | +0.11±0.09  | 11.0±2.2  | 11.0±2.2 | seismic period |
| 9955598 | 0.96±0.01 | 6.43±0.47    | 4.506 5307   | 0.89±0.01  | 6.98±0.45 | 5250 | 5460±75 | +0.08±0.10  | 34.7±4.3  | 34.7±4.3 | KOI      |
| 1045111 | 1.19±0.04 | 2.03±0.29    | 4.315 6138   | 1.15±0.03  | 2.86±0.54 | 6095 | 6120±84 | -0.06±0.09  | 14.6±1.1  | 14.6±1.1 | seismic period |
| 10586004 | 1.16±0.05 | 6.35±1.37    | 4.072 5943   | 1.18±0.03  | 6.43±0.62 | 5753 | 5770±83 | +0.29±0.10  | 29.8±1.0  | 29.8±1.0 | KOI      |
| 10644253 | 1.13±0.05 | 1.07±0.25    | 4.402 6001   | 1.16±0.02  | 1.20±0.39 | 5991 | 6030±84 | +0.12±0.09  | 10.9±0.87 | 10.9±0.87 | KOI      |
| 10963065 | 1.07±0.02 | 4.360±0.46   | 4.294 6063   | 1.09±0.02  | 4.18±0.44 | 6076 | 6104±74 | -0.20±0.10  | 12.4±1.2  | 12.4±1.2 | KOI      |
| 11244118 | 1.10±0.05 | 6.43±0.58    | 4.077 6023   | 1.13±0.02  | 6.90±0.44 | 5677 | 5745±84 | +0.35±0.09  | 23.2±3.9  | 23.2±3.9 | seismic period |
| 11401755 | 1.03±0.05 | 5.85±0.93    | 4.043 6094   | 1.06±0.03  | 7.10±0.60 | 6057 | 5911±66 | -0.20±0.06  | 17.2±1.4  | 17.2±1.4 | KOI      |

Unit are as follows: mass, solar masses; age, Gyr; log(g), g cm^{-2}; T_{eff}, K; period, days. Quoted errors are given to 1σ.