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SUPPLEMENTARY INFORMATION

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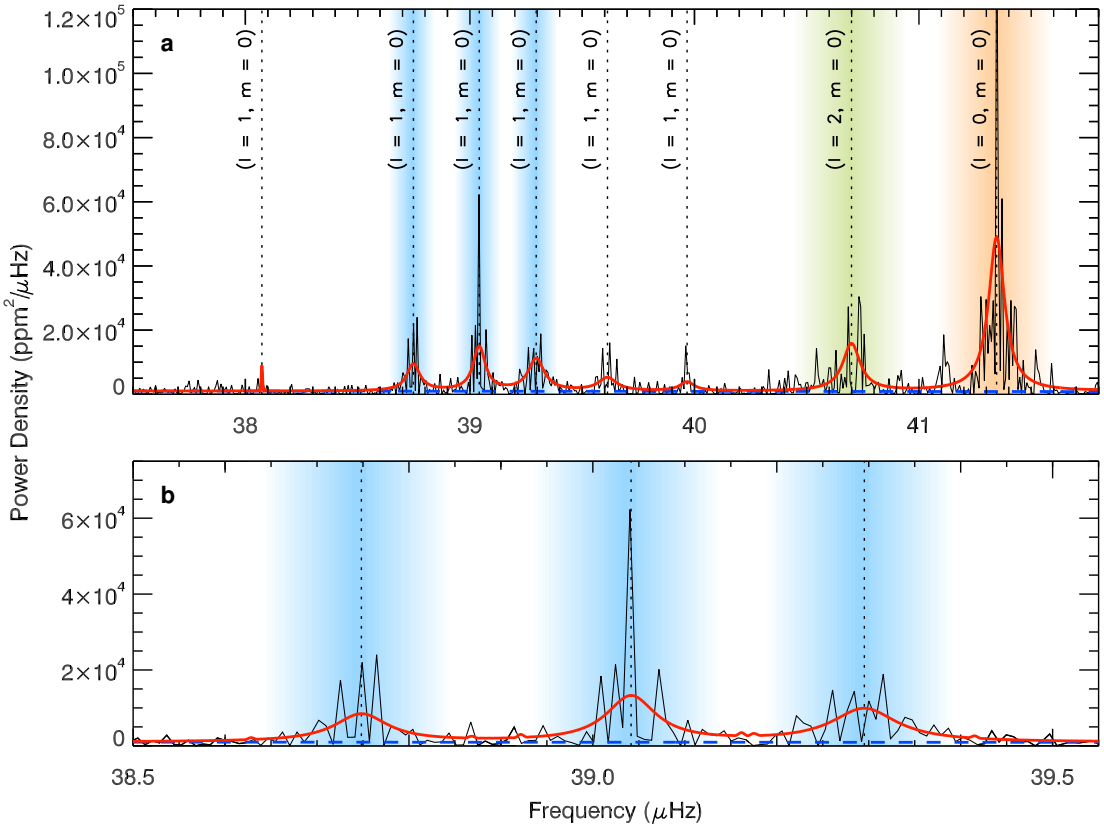
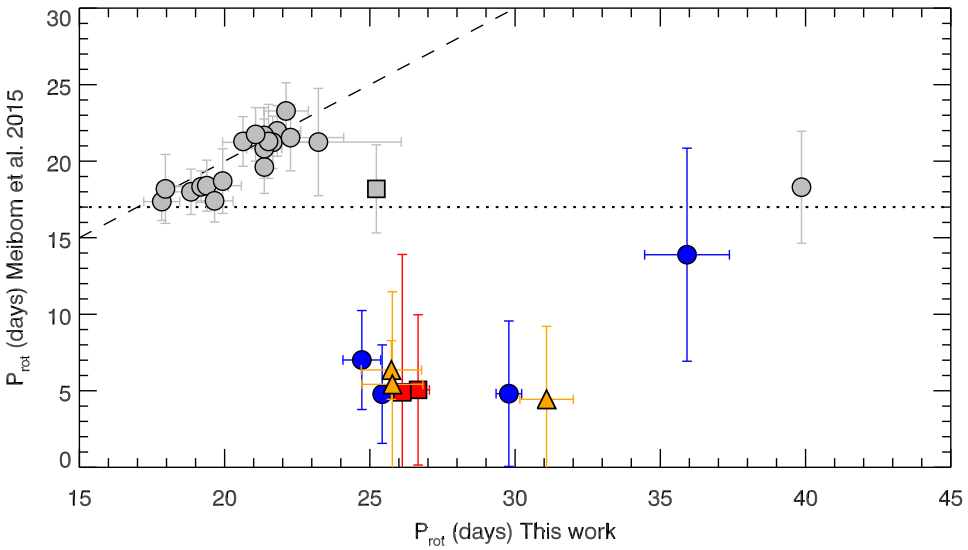
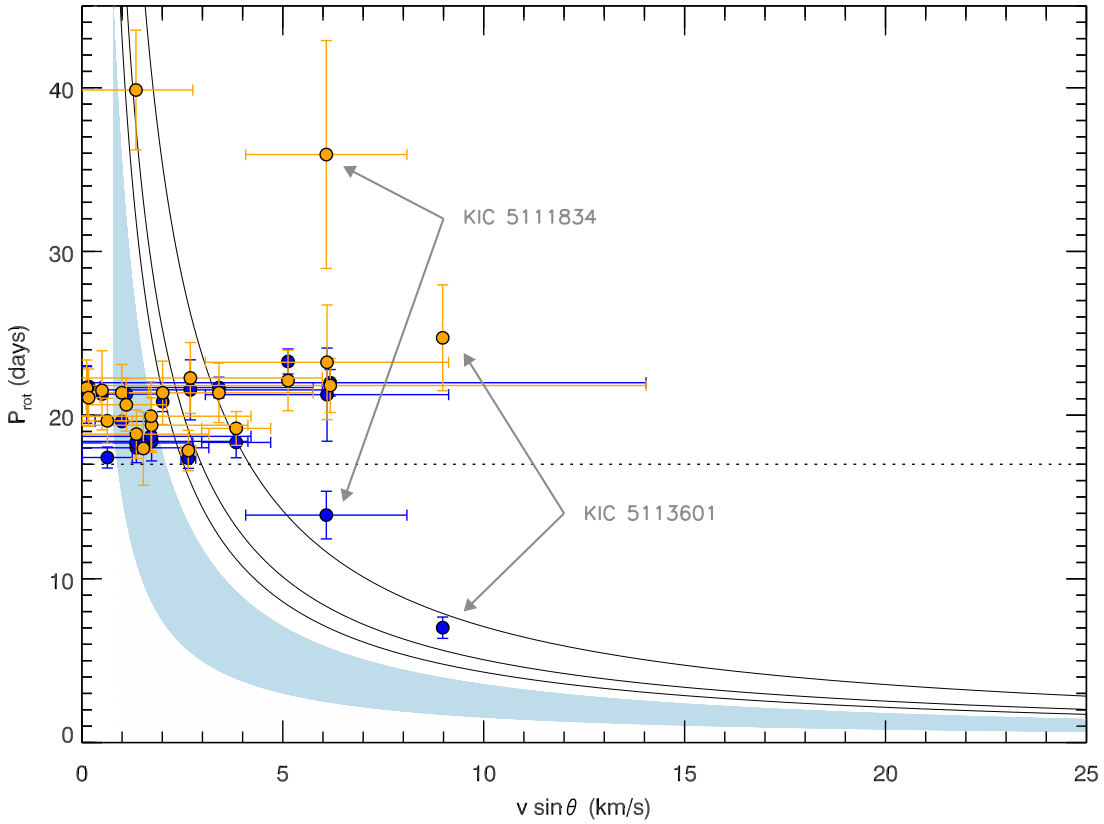
Spin alignment of stars in old open clusters



Supplementary Figure 1 | **Bayesian peak bagging analysis and fit to the inclination angle. a**, A chunk of power spectrum for the core-He-burning red giant KIC 5112373 having a low inclination angle. The Bayesian fit to the oscillations[18,19] is indicated by the red line, with the individual mode frequencies marked by a vertical dotted line and the mode identification by labels. The green and orange vertical bands highlight the regions containing the quadrupole ($l = 2$) and radial ($l = 0$) modes, respectively. The blue bands indicate the three dipolar mixed modes used to fit the inclination angle of the stellar spin (see Methods). The dashed blue line shows the level of the background signal. **b**, A close-up in the region containing the three dipolar mixed modes marked by a blue vertical band, with the red line here showing the resulting Bayesian fit to the inclination angle.



Supplementary Figure 2 | Comparison of new rotation periods with published values for 30 stars in NGC 6819. The published rotational periods[20] are compared with the results from our new reanalysis of the same targets (see Methods for more details). Colored symbols correspond to stars discussed in the text (blue circles for clear detection, red squares for unreliable detection, orange triangles for polluted). KIC 4938993, one of the polluted targets, is not displayed because no period measurement could be obtained for this star. The dashed line corresponds to a one-to-one match while the dotted line delimits the threshold of the fast rotating stars selected in this work, $P_{\rm rot} = 17$ days. All symbols shown in gray correspond to stars with $P_{\rm rot} > 17$ days (circles for clear detections and a square for KIC 5024856, the only slow rotating star with unreliable detection).



Supplementary Figure 3 | Rotation periods versus published projected equatorial velocities for 21 stars in NGC 6819. The published rotational periods[20] (blue circles) are compared to those from our analysis (orange circles) for the stars found to have reliable period detections (see Methods). The published $v \sin\theta$ measurements[20] are kept the same for both sets of period measurements. The horizontal dotted line delimits the threshold of the fast rotating stars discussed here, $P_{\rm rot} = 17$ days. The only two fast rotating stars with reliable period detection from our analysis are indicated by arrows, with KIC IDs overlaid. Tracks at constant radii ($R = 0.85, 1.0, 1.4\,R_\odot$) and inclination angle $\theta = 90°$ are shown. The shaded region delimits a regime of low spin inclination ($\theta = 20$-$30°$) and stellar radius $0.85\,R_\odot \leq R \leq 1.4\,R_\odot$.

KIC ID	Right Ascension (deg)	Declination (deg)	θ (deg)	$\overline{\delta\nu_{\rm rot}}$ (μHz)	Evolutionary stage
2297384	290.1899	37.6641	36^{+3}_{-3}	0.055	RC
2297825	290.2701	37.6843	48^{+4}_{-4}	0.050	RC
2436417	290.1452	37.7750	37^{+3}_{-3}	0.063	RC
2436676	290.1697	37.7912	18^{+6}_{-6}	0.250	RGB
2436732	290.1749	37.7984	37^{+3}_{-3}	0.072	RC
2436818	290.1818	37.7349	13^{+6}_{-5}	0.180	RGB
2437103	290.2031	37.7868	39^{+4}_{-4}	0.121	RC
2437270	290.2143	37.7780	26^{+5}_{-4}	0.122	RGB
2437325	290.2185	37.7876	11^{+5}_{-5}	0.150	RGB
2437353	290.2203	37.7592	47^{+3}_{-3}	0.066	RC
2437564	290.2346	37.7426	30^{+3}_{-3}	0.070	RC
2437804	290.2536	37.7594	8^{+5}_{-5}	0.050	RC
2437933	290.2645	37.7771	20^{+5}_{-5}	0.200	RGB
2437957	290.2674	37.7730	38^{+3}_{-3}	0.184	RGB
2437972	290.2684	37.7694	8^{+4}_{-4}	0.150	RGB
2437976	290.2690	37.7815	0^{+10}_{-10}	0.180	RGB
2437987	290.2697	37.7656	38^{+3}_{-3}	0.057	RC
2438038	290.2748	37.7994	36^{+3}_{-3}	0.045	RGB
2438051	290.2762	37.7499	30^{+4}_{-4}	0.062	RC
2438333	290.3042	37.7168	14^{+3}_{-3}	0.080	RGB
2569055	290.1252	37.8387	20^{+6}_{-5}	0.120	RC
2569945	290.2237	37.8399	31^{+3}_{-3}	0.083	RC
2570094	290.2404	37.8170	28^{+3}_{-3}	0.066	RGB
2570244	290.2560	37.8014	20^{+3}_{-3}	0.172	RGB
2570384	290.2752	37.8680	29^{+4}_{-4}	0.040	RGB

Supplementary Table 1 | **Positions and stellar-spin inclinations for the red giants of NGC 6791.** All the declinations and right ascensions refer to the astronomical epoch J2000. The inclination angles are the median values, with corresponding 68.3 % credible intervals, obtained from a Bayesian parameter estimation (see Methods). The average rotational splitting, $\overline{\delta\nu_{\rm rot}}$, is a reference value per star. The evolutionary stage distinguishes between core-He-burning (RC) and shell-H-burning red giants (RGB), and it is derived from the available period spacings used for the peak bagging analysis[16,30,31].

KIC ID	Right Ascension (deg)	Declination (deg)	θ (deg)	$\overline{\delta\nu}_{\rm rot}$ (μHz)	Evolutionary stage
4937056*	295.3180	40.0975	68^{+5}_{-5}	0.084	RC
4937770	295.4766	40.0360	28^{+3}_{-3}	0.265	RC
5023953	295.2415	40.1382	29^{+4}_{-4}	0.204	RC
5024327	295.3061	40.1989	33^{+3}_{-3}	0.112	RC
5024404	295.3152	40.1696	80^{+10}_{-4}	0.125	RC
5024414*	295.3164	40.1865	26^{+5}_{-4}	0.351	RC
5024476*	295.3240	40.1544	20^{+7}_{-6}	0.180	RC
5024582*	295.3389	40.1992	29^{+4}_{-4}	0.141	RC
5111718	295.1535	40.2548	64^{+4}_{-4}	0.249	RGB
5111949	295.2092	40.2197	0^{+11}_{-11}	0.200	RC
5112072	295.2334	40.2277	77^{+6}_{-7}	0.220	RGB
5112361*	295.2841	40.2524	0^{+7}_{-7}	0.150	RGB
5112373	295.2858	40.2250	20^{+8}_{-6}	0.120	RC
5112387	295.2886	40.2455	17^{+8}_{-7}	0.150	RC
5112401	295.2913	40.2638	16^{+9}_{-8}	0.080	RC
5112467	295.3033	40.2066	28^{+6}_{-4}	0.137	RC
5112491	295.3065	40.2057	17^{+8}_{-8}	0.150	RC
5112730	295.3395	40.2326	14^{+8}_{-8}	0.120	RC
5112938	295.3715	40.2178	16^{+9}_{-8}	0.120	RC
5112950	295.3731	40.2059	15^{+8}_{-7}	0.170	RC
5112974	295.3762	40.2561	16^{+8}_{-6}	0.150	RC
5113441	295.4610	40.2670	10^{+5}_{-9}	0.500	RGB
5200152	295.3494	40.3624	26^{+6}_{-5}	0.149	RC

Supplementary Table 2 | Positions and stellar-spin inclinations for the red giants of NGC 6819. All the declinations and right ascensions refer to the astronomical epoch J2000. The inclination angles are the median values, with corresponding 68.3 % credible intervals, obtained from a Bayesian parameter estimation (see Methods). The average rotational splitting, $\overline{\delta\nu}_{\rm rot}$, is a reference value per star. The evolutionary stage distinguishes between core-He-burning (RC) and shell-H-burning red giants (RGB), and it is derived from the available period spacings used for the peak bagging analysis[16,30,31]. The stars marked with an asterisk are the spectroscopic single-lined binaries[29] indicated in Fig. 1 and 2.

Simulation #	$E_{\rm ther}/E_{\rm grav}$	$E_{\rm tur}/E_{\rm grav}$	$E_{\rm rot}/E_{\rm grav}$	α
1	0.0025	1.51	0	0.40
2	0.0025	1.12	0.15	0.48
3	0.0025	0.46	0.15	0.45
4	0.0025	0.15	0.15	0.59

Supplementary Table 3 | **Energy balancing and alignment parameters of the simulations.** The simulated molecular cloud has a mass of $10^3\,M_\odot$ and a radius of $0.084\,$pc. The various forms of energy used for the different simulations are reported in relative values for the portion of molecular cloud forming the protocluster (containing about $140\,M_\odot$). The thermal energy $E_{\rm ther}$, turbulent kinetic energy $E_{\rm tur}$, and rotational kinetic energy $E_{\rm rot}$, counteract the gravitational potential energy $E_{\rm grav}$ and provide global support for the collapsing cloud. The alignment coefficient α is computed according to its definition (see Methods). All the simulations were run until 25 stars with $M \geq 0.7\,M_\odot$ are formed.

N	α	Skewness
17	0.415 ± 0.071	2.187
19	0.410 ± 0.068	2.165
23	0.402 ± 0.062	2.278
25	0.400 ± 0.060	2.374
36	0.390 ± 0.047	2.005

Supplementary Table 4 | **Alignment coefficients from simulations of uniform stellar-spin inclination.** The most likely alignment coefficient α and its 1σ uncertainty are computed from a skewed Gaussian probability distribution. The distributions are each obtained from 10000 simulations of random stellar-spin orientation in three dimensions. Each distribution corresponds to a different number of stars, N. The adopted numbers of stars are chosen according to those from the observations.

KIC ID	θ (deg)	$\overline{\delta\nu_{\rm rot}}$ (μHz)	Evolutionary stage
3662421	83^{+2}_{-2}	0.163	RC
3744043	37^{+3}_{-3}	0.182	RGB
3954857	86^{+4}_{-2}	0.149	RC
3965149	42^{+6}_{-6}	0.096	RC
4253026	75^{+2}_{-2}	0.108	RC
5709182	38^{+3}_{-3}	0.084	RC
6117517	18^{+3}_{-3}	0.274	RGB
6144777	61^{+2}_{-2}	0.177	RGB
6363338	90^{+4}_{-4}	0.170	RC
6535641	24^{+5}_{-5}	0.040	RC
6604616	90^{+4}_{-4}	0.093	RC
6936990	72^{+3}_{-3}	0.058	RC
7025568	42^{+2}_{-2}	0.149	RC
7060732	79^{+1}_{-1}	0.225	RGB
7619745	90^{+8}_{-8}	0.228	RGB
8366239	74^{+3}_{-3}	0.149	RGB
8475025	90^{+3}_{-3}	0.229	RGB
8547122	83^{+5}_{-4}	0.091	RC
8718745	23^{+2}_{-2}	0.287	RGB
9145955	10^{+6}_{-6}	0.180	RGB
9267654	90^{+3}_{-3}	0.312	RGB
9412305	58^{+5}_{-5}	0.081	RC
9475697	32^{+3}_{-3}	0.222	RGB
9779708	38^{+3}_{-3}	0.045	RC
9882316	0^{+6}_{-6}	0.400	RGB
9907009	46^{+4}_{-4}	0.058	RC
10014635	30^{+3}_{-4}	0.082	RC
10123207	0^{+3}_{-3}	0.400	RGB
10200377	0^{+3}_{-3}	0.300	RGB
10257278	84^{+4}_{-3}	0.332	RGB
11200291	28^{+3}_{-3}	0.042	RC
11353313	72^{+2}_{-2}	0.346	RGB
11570459	54^{+3}_{-3}	0.052	RC
11913545	90^{+5}_{-5}	0.196	RGB
11968334	56^{+2}_{-2}	0.283	RGB
12008916	90^{+5}_{-5}	0.299	RGB

Supplementary Table 5 | Stellar-spin inclinations for the control sample of field red giants. The control sample includes the 19 shell-H-burning red giants with detailed peak bagging parameters already available[19], and additional 17 core-He-burning red giants[36]. All the inclination angles were measured using the same approach as for the cluster stars. The inclination angles are the median values, with corresponding 68.3 % credible intervals, obtained from a Bayesian parameter estimation (see Methods). The evolutionary stage is obtained from published period spacings[19,31,35]. The average rotational splitting, $\overline{\delta\nu_{\rm rot}}$, is a reference value per star.