Surface rotation and magnetic activity of solar-like stars observed by the *Kepler* mission

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Abstract: Stars with an external convective envelope have rotation periods that evolve as the square root of the age on the main sequence. This led to empirical "gyrochronology" relations, which should allow us to determine the age of a star from its surface rotation period. Recently, the exquisite *Kepler* data showed that there is a stalling of the magnetic braking. This was based on the measurement of surface rotation based on the light curve modulation related to the passage of spot on the visible stellar disks.

Here, we present the analysis of more than 100,000 of solar-like main-sequence stars (F, G, K, M dwarfs) observed in long cadence for 4 years with the Kepler mission, leading to the largest catalog of rotation periods available for more than 40,000 dwarfs along with their proxies for magnetic activity. We apply our improved rotation pipeline, which combines three different methods (time-frequency analysis, auto-correlation function and composite spectrum) with different calibrations. For K and M dwarfs, we obtained more than 15,000 rotation periods, including new periods for ~4,000 stars. For F and G dwarfs, we implemented a machine learning algorithm to automatically select the reliable rotation periods and reduce visual checks.

Finally, we know for the Sun and many solar-like stars, magnetic activity can suppress the amplitude of the acoustic modes. We analyzed ~1,000 solar-like stars observed in short-cadence during the Kepler survey phase where modes were undetected. Surprisingly magnetic activity might not the main reason for not detecting modes in those stars.

Context: Gyrochronology

- For 2 young clusters and the Sun and based on:
  - Rotation
  - Magnetic activity
  - Lithium

Derived a law with age:

$$\boxed{P_{rot} \sim \tau^{-1/2}}$$

[e.g. Skumanich 1972;Kawaler (1988); MacGregor & Brenner (1991)]

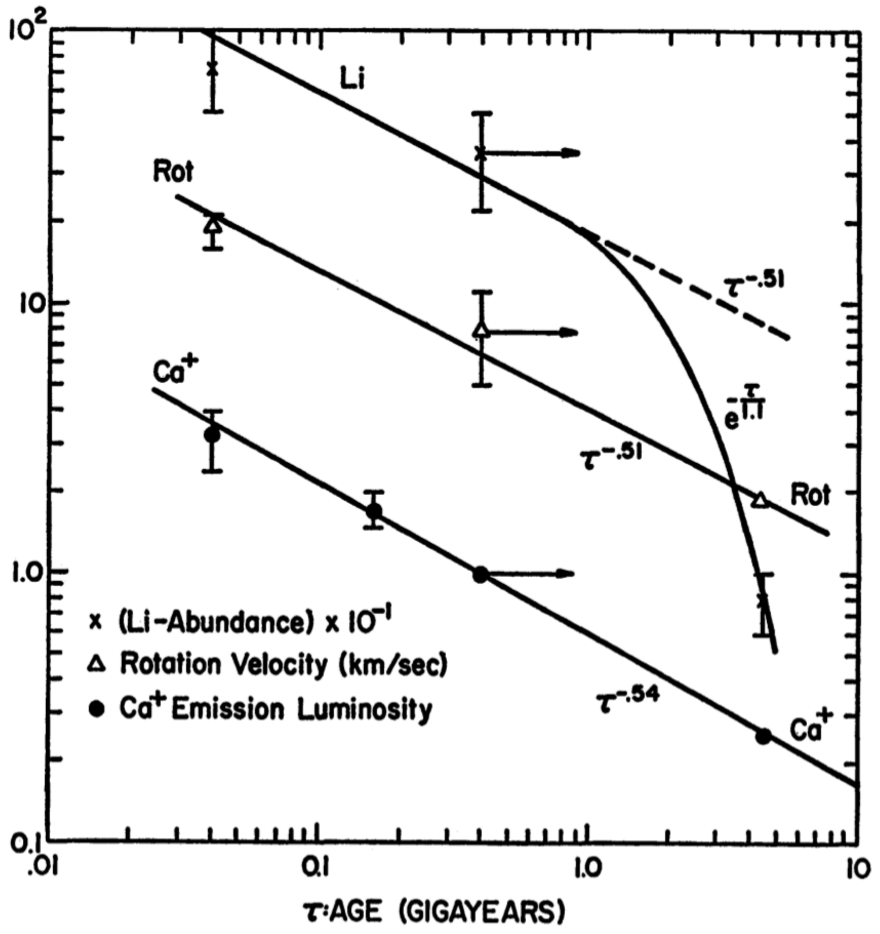
$$\left(\frac{dJ}{dt}\right)_{\rm wind} = K_W \left(\frac{R_*/R_\odot}{M_*/M_\odot}\right)^{1/2} \Omega_*^3,$$

- BUT dependency with the stellar mass

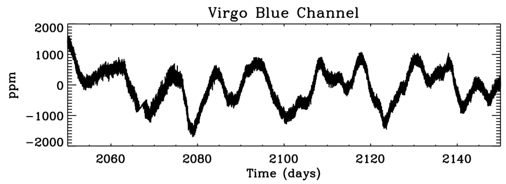
[e.g. Kraft, 1967; Epstein & Pinsonneault, 2013]

$M > 1.25 M_\odot$: faster rotation

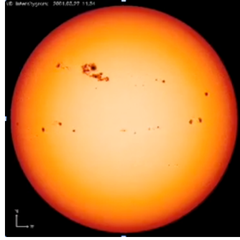
- *Kepler* data: magnetic braking stops for a given Rossby number. [van Saders et al. 2016]



[Skumanich 1972]

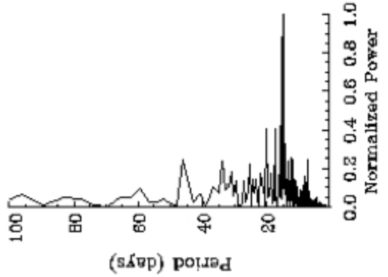


Methodology: photometric data

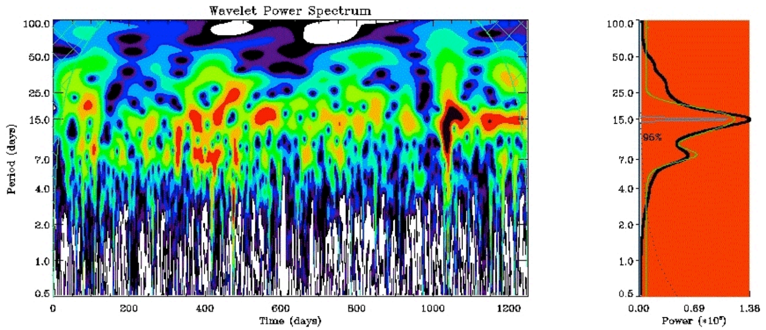


Measuring Surface Rotation:

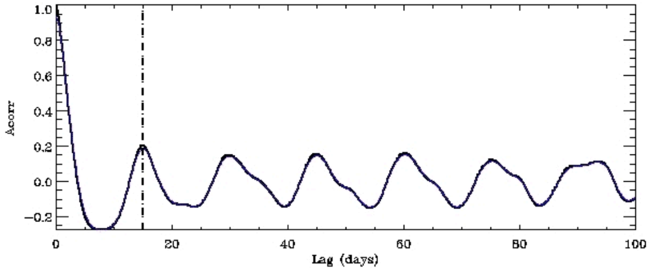
- Periodogram
  [Nielsen et al. 2013,
  Reinhold et al. 2013]



- Time-frequency
  [Mathur et al. 2010; Ballot et al. 2011; Mathur et al. 2014]



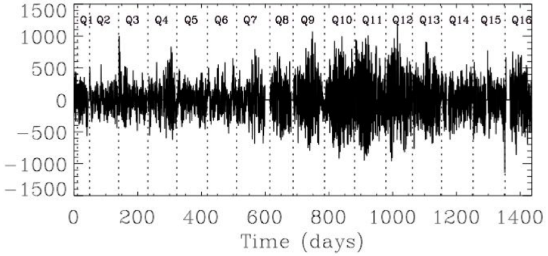
- Auto-correlation
  [McQuillan et al. 2013a, b;
  García et al. 2014]



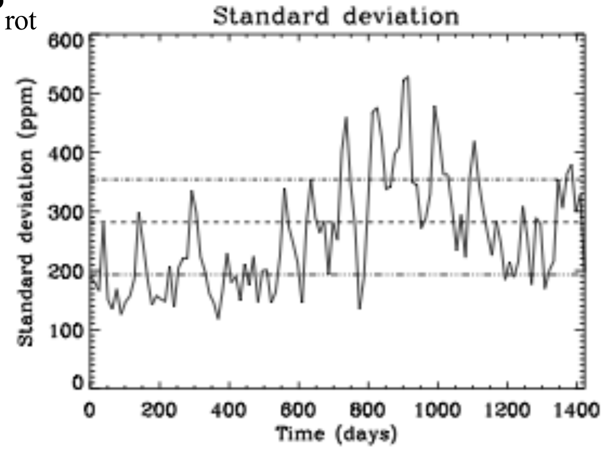
Wavelet/ACF: "best method in terms of completeness and reliability" [Aigrain et al. 2015]

Photometric activity indexes:

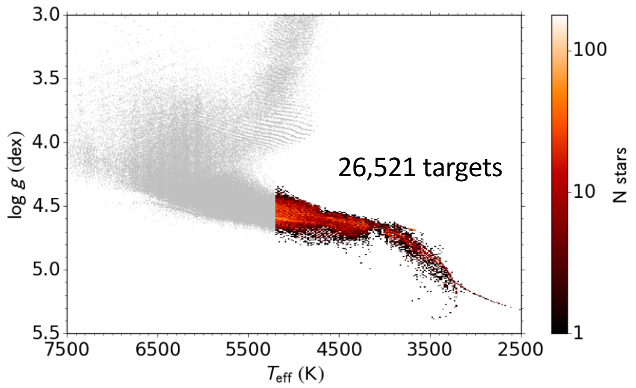
- Standard deviation of time series: S_{ph}
  [García et al. 2010]



- Global index: $< S_{ph} >$
  Subseries of length 5 x P_{rot}
  [Mathur et al., 2014b, A&A
  Mathur et al. 2014b, JSWC]



Validated by comparison with other classical solar indexes [Salabert et al. 2018]



Kepler K and M dwarfs results

✓ Automatic and visual selection yield

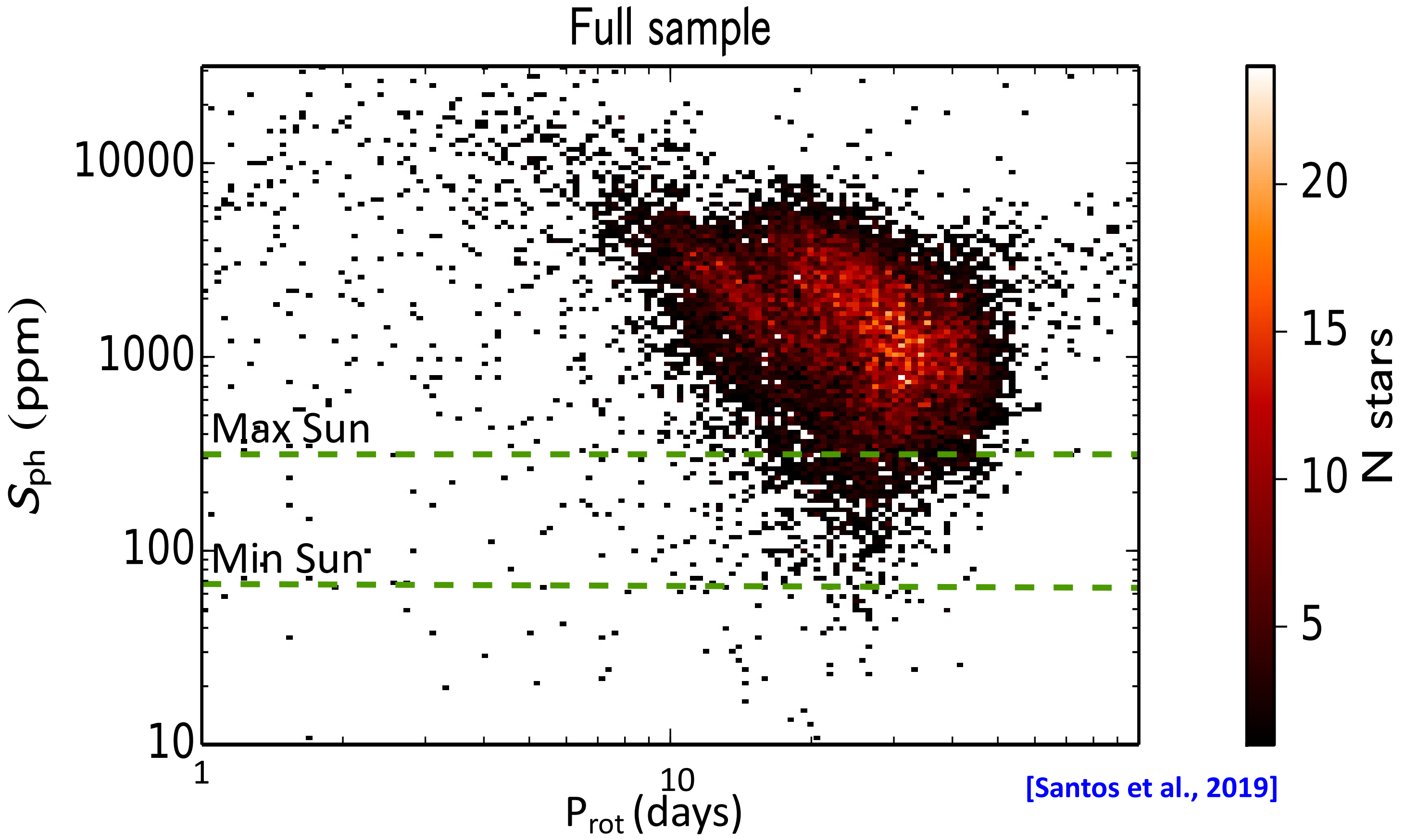
➢ 15,290 detections (>60%)

✓ Comparison with literature:

- ~70% of stars in common with McQuillan et al. (2014)
  - Agreement within 2 sigma for 99.4% of the targets
- New rotation periods reported for 4431 stars
- Fainter and cooler stars

➢ Implementing **Machine Learning** techniques to reduce visual checks

[Breton et al., in prep.]



[Santos et al., 2019]

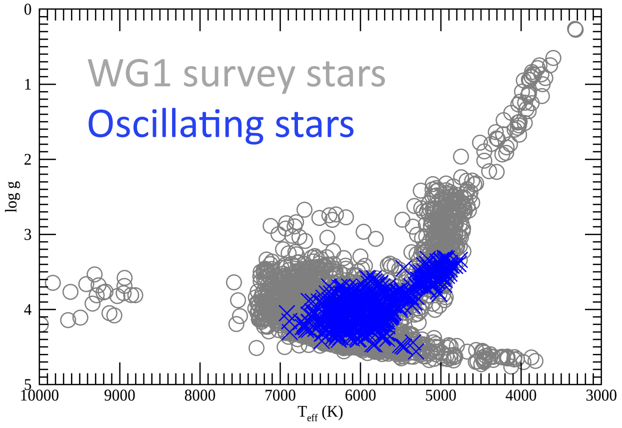
✓ Stars rotating faster are more active

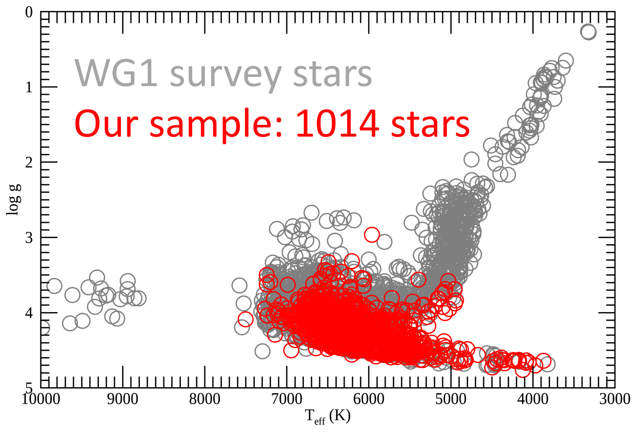
✓ K and M dwarfs are more active than the Sun

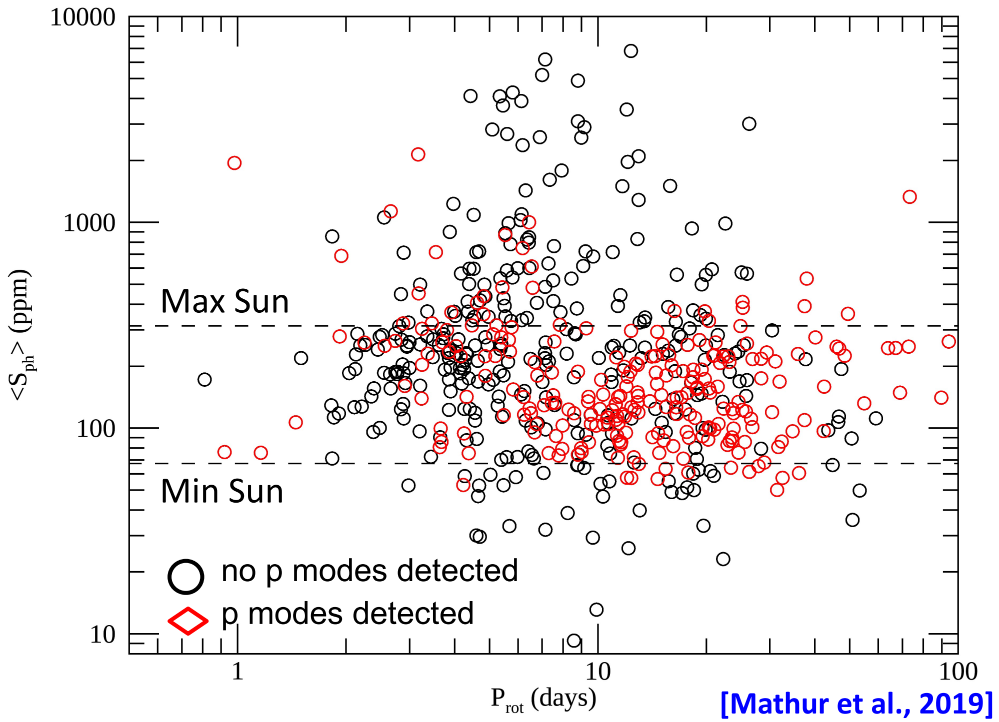
Kepler non-oscillating solar-like stars

- *Kepler* Survey phase: 2,576 stars observed in short cadence as part of WG1
- Solar-like oscillations detected in 518 stars
- Why did we not detect oscillations in the remaining stars?
- Chaplin et al. (2011): magnetic activity
- But sample contained some red giants, classical pulsators, new detections of oscillations from newly calibrated data

→ Cleaned sample of 1014 stars





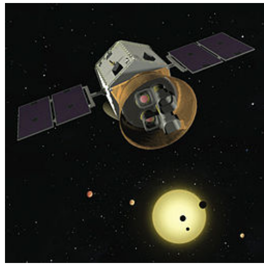


[Mathur et al., 2019]

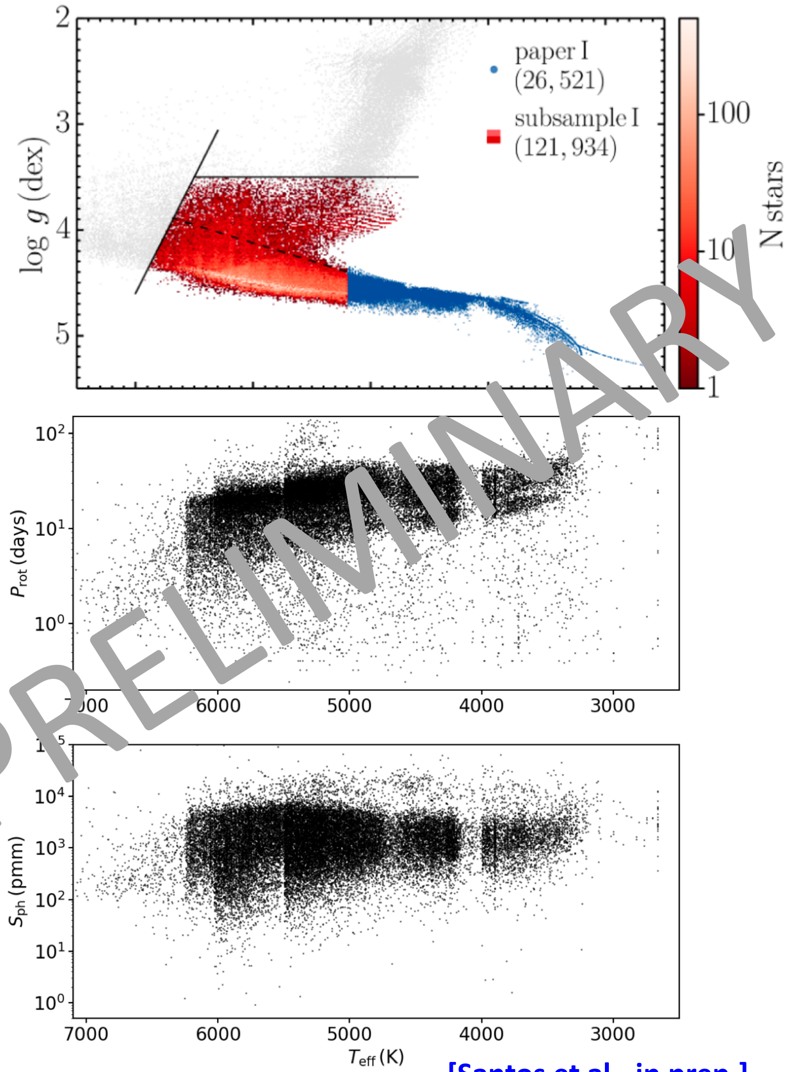
For a sample of stars with predicted high amplitude of modes:

- Reliable rotation for 323 stars
- 32% of stars are above the maximum level of the Sun.
- Fe/H, binarity, inclination angle impact?: too small sample to conclude
- Overestimation of the predicted amplitude of the modes?

Impact & Future prospects



- Rotation periods measured for *Kepler* data:
  - Crucial to understand angular momentum transport from dwarfs to giants and improve stellar parameters determination (e.g. age)
- In the process of analyzing ~120,000 stars (F and G dwarfs and subgiants):
  - Preliminary results with Machine Learning: ~15,000 additional rotation periods compared to what is published
- Analyze TESS lightcurves and in preparation for the ESA mission PLATO
- Non-oscillating stars:
  - Improve the prediction of acoustic modes amplitudes for TESS and PLATO



[Santos et al., in prep.]

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