Stellar Rotation in the Kepler era

From rotation periods to stellar ages

Timo Reinhold
Solar & Stellar Interiors, IAG

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Long time ago...

- Telescope: invented ~ 1608
- Galilei discovered dark spots on the Sun
- Many others followed: T. Harriot, J. & D. Fabricius, C. Scheiner...
Sun spot observations

Thomas Harriot

Christoph Scheiner
Sun spots today
From the Sun to the stars

- Problem: Cannot resolve spots on distant stars
- But: Star spots cause (periodic) variability in stellar light curves
- High-precision light curves from space telescopes: MOST, CoRoT, Kepler, (PLATO)

→ achieve stellar rotation periods!
Star spots today

- CoRoT-2 light curve: periodic variability due to star spots
- Beat-shape: More than only one rotation period!

→ Differential rotation (DR)
Stellar rotation ↔ Chromospheric activity

- Spotted star
  - (strong) magnetic fields
  - Magnetic field heats the chromosphere
  - Chromospheric emission
- Mount Wilson H-K project (1980): Rotation period & chromospheric activity
  - Use CaII H & K as rotation indicator
Activity-rotation relation

- $\log R'_\text{HK}$ vs. Rossby number for Mount Wilson stars: closed (young), open (old) stars
- Activity increases toward fast rotators

Noyes (1984)
Activity-age relation

- Activity index
  \[ \log R'_HK \]
  vs. stellar age \( t \) for visual binaries, single F stars & open clusters
- Activity decreases with age

Soderblom, Duncan & Johnson (1991)
Age-rotation-activity relation

- Skumanich showed a relation between activity (CaII), age (Li), and rotation rate.

- All trends \( \sim t^{-1/2} \)
Kepler Roadmap

- Measure (mean) rotation period
  → esp. account for differential rotation
- Use rotation-mass-age relations (Gyrochronology)
  → yield stellar ages + errors
Data & Methods
Active Kepler stars

KIC: 1995351

KIC: 2020830

KIC: 1869783

BJD – 2454833 (d)
Use variability range

[Graphs showing time series data for KIC: 891916 and KIC: 1867358, with variability range indicated.]

KIC: 891916

KIC: 1867358
How many active stars?

Active: 24.6 % of all stars

Active stars

Not considered

Active - Sun

$\log_{10} R_{\text{var}} [%]$

# of stars

$2.0 \times 10^4$

$1.5 \times 10^4$

$1.0 \times 10^4$

$5.0 \times 10^3$

$0$

$-2.0$

$-1.5$

$-1.0$

$-0.5$

$0$

$0.5$
How to measure periods?
→ Lomb-Scargle periodogram
Define Periods

- Period with highest peak: P1
- Search for 2nd period adjacent (±30%) to P1
- If present: P2 (2nd highest peak)
- **Problem:** Periods change with time!
  - → Compare different segments of the light curve
  - → Use mean periods!
Quarterly P1 change

KIC: 2142372

KIC: 9411323
Quarterly light curve & periodogram change
Q9-Q12 Segment
Q5-Q12 Segment
Full light curve
Rotation
Color vs. rotation period

![Graph showing the relationship between mass and color index (B-V) for different rotation periods (P_1)](image-url)
Color vs. rotation period

![Graph showing the relationship between color and rotation period with data points from Baliunas (1996) and Kiraga & Stepien (2007).]
Color vs. rotation period

![Graph showing the relationship between color index (B-V) and rotation period (P) for stars of different masses. The graph includes data points from Baliunas (1996), Kiraga & Stepień (2007), and Irwin (2011).]
Color vs. rotation period
Color vs. rotation period
Color vs. rotation period

![Graph showing the relationship between color and rotation period.](image_url)
Teff vs. rotation period

McQuillan et al. (2014)
Kepler results

Measured rotation periods with Kepler:

- McQuillan et al. (2013a): 1570 (M dwarfs)
- Nielsen et al. (2013): 12.151 stars
- McQuillan et al. (2013b): 737 (KOI)
- Walkowicz & Basri (2013): 950 (KOI)
- Reinhold et al. (2013): 24.124 stars
- McQuillan et al. (2014): 34.030 stars!!!
Gyrochronology

- First introduced by Sydney Barnes (2003)
- Method based on rotational braking due to stellar winds
- Uses open clusters: ages known
- Measure B-V color & rotation period
- Yield color - period – age relation!

→ Calculate ages of field stars!
Rotational braking
Problems...

- Calibration for young FGK stars mostly
- Older stars: The Sun (age known); ages for Mount Wilson stars from activity-age relations
- Error sources:
  - Differential rotation
  - Initial range of rotation periods
  - Kepler: No B-V color
Differential Rotation
Quantities

- Most light curves: 2 periods found
- Sort periods according $P_1 < P_2$ and compute DR quantities:
  - Relative DR: $\alpha = (P_2 - P_1)/P_2$
  - Absolute DR: $d\Omega = 2\pi(1/P_1 - 1/P_2)$
- How do these quantities correlate with Teff & $P_{min}$?
Pmin vs. alpha

Total: 17334 stars

Detection limit

- $T > 7000$: black
- $6000 < T \leq 7000$: green
- $5000 < T \leq 6000$: yellow
- $4000 < T \leq 5000$: orange
- $3000 < T \leq 4000$: purple

$p_{\min} [d]$
P_{\text{min}} \text{ vs. } d\Omega
Teff vs. dOmega

Total: 17334 stars

- Barnes (2005)
- Ammler-von Eiff & Reiners (2012)
- Cameron (2007)
- Kueker & Ruediger (2011)
- detection limit

\begin{itemize}
\item $d\Omega$ [rad d$^{-1}$]
\item $T_{\text{eff}}$ [K]
\end{itemize}
Stellar Ages
Gyro ages

![Graph showing gyro ages with different calibration methods: B07, MH08, M09. The x-axis represents log(Age) in Myr, and the y-axis shows the number of stars. There is a peak at around log(Age) = 3.5, indicating the age of the Sun (4500 Myr).]
Gyro vs. Astero Ages
Conclusions

- Mean rotation period: Well known for many stars!
- DR: Exact values not well known for many stars because
  - peaks change over time (DR, spot evolution, instr. effects)
    → range of rotation periods for the same star
- Ages: Gyrochronology provides most reliable ages for young-mid age field stars
  - DR induces error in age
  - **Problem:** old stars (age > 2 Gyr)