Building Precision Stellar Clocks
with *Kepler* and *Gaia*

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with
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and
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together with
Ruth Angus, John Brewer, Ann Marie Cody, Kevin Covey, Nicholas Law, Sean Matt, Søren Meibom, Rayna Rampalli, Steve Saar, Jennifer van Saders, Andrew Vanderburg, Jason T. Wright, and many others that contributed to The Ruprecht 147 Project!

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Kepler and K2 provide the light curves

Ruprecht 147
NGC 752
Hyades

NGC 6819
Praesepe

M67

NGC 6811

M34

M35

M37

Pleiades

3 campaigns for a K0 dwarf in Praesepe

1 quarter for this M0 dwarf in NGC 6811

See Poster 89 by Rayna Rampalli
Gaia finds single-star members of star clusters. $P_{\text{rot}}$ distributions are now incredibly tight.

Praesepe (670 Myr)

Sun (4.567 Gyr)

Praesepe periods (Douglas et al. 2017)
A simple spin-down model with Praesepe and the Sun

Stars spin down continuously with a braking index that is constant in time and common to all stars.

\[ P_{\text{rot}} = f(M_\star) \times t^n \]

Praesepe (670 Myr) 
+ 
Sun (4.567 Gyr)

\[ n = 0.61 \]

Praesepe periods (Douglas et al. 2017), Braking index calculation (Douglas+prep, Angus+prep)
Gyrochronology reveals ages for *Kepler* rotators

Ages: 100 Myr, 1 Gyr, 4 Gyr, 6 Gyr

*Kepler* periods (McQuillan et al. 2014)

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No gyrochronology model describes all cluster data.

(Angus et al. 2015, Agüeros et al. 2018)

...not even the Hyades using the Praesepe model

(Douglas & Curtis et al., submitted)
Gyrochronology fails to describe K dwarf spin-down

Data from Rebull et al. (2016)

Data from Meibom et al. (2011)

See results from Meibom et al. (2009, 2011a, 2011b) for M34, M35, NGC 6811

Pleiades (125 Myr)

NGC 6811 (1 Gyr)
Gyrochronology fails to describe K dwarf spin-down

**Pleiades (125 Myr)**

- 670 Myr Praesepe
- 125 Myr Pleiades
- 125 Myr Praesepe-Sun Model

**NGC 6811 (1 Gyr)**

- 1000 Myr NGC 6811
- 670 Myr Praesepe
- 125 Myr Praesepe-Sun Model

Why so flat?

Data from Rebull et al. (2016)

Data from Meibom et al. (2011)

See results from Meibom et al. (2009, 2011a, 2011b) for M34, M35, NGC 6811

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Gyrochronology fails to describe K dwarf spin-down

Pleiades (125 Myr)

NGC 6811 (1 Gyr)

Data from Rebull et al. (2016)

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See results from Meibom et al. (2009, 2011a, 2011b) for M34, M35, NGC 6811

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A Temporary Epoch of Stalled Spin-down for Low-Mass Stars: Insights From NGC 6811 with *Kepler* and *Gaia*

Jason L. Curtis, Marcel A. Agüeros, Stephanie T. Douglas, and Søren Meibom
Submitted to *ApJ*

Single-star members are instantly identified from *Gaia* astrometry and photometry.
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M0 dwarf!
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![Graph showing rotation period vs. effective temperature for Meibom et al. (2011) sample and the author's sample.](image)

Meibom et al. (2011) sample

Extends from early-K…

…to M0!

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Benchmark Cluster Rotators

Johnson & Sandage (1955)
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Jason L. Curtis, Marcel A. Agüeros, Stephanie T. Douglas, and Søren Meibom
Submitted to ApJ

Benchmark Cluster Rotators

Differential gyrochronology age Of NGC 6811 relative to Praesepe

K’s did not slow down:

Jason L. Curtis, Marcel A. Agüeros, Stephanie T. Douglas, and Søren Meibom
Submitted to ApJ

Jason Lee Curtis jasoncurts.astro@gmail.com @jasonleecurtis_
A Temporary Epoch of Stalled Spin-down for Low-Mass Stars: Insights From NGC 6811 with Kepler and Gaia

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Submitted to ApJ

A color-dependent braking index from NGC 6811 and Praesepe

The Universe is not old enough for color-dependent braking

Kepler field distribution

Age of Universe, 13.7 Gyr

Praesepe, 670 Myr

Kepler periods (McQuillan et al. 2014)
What could stall spin-down?

(A) Inside: envelope taps into core angular momentum
    (e.g., Gallet & Bouvier et al. 2013, 2015)

(B) Outside: magnetic braking becomes inefficient

Can we fix empirical models while we wait?
The K2 Survey of Ruprecht 147 (GO 7035)

Gaia DR2 Astrometry and Photometry

Spectroscopy and Radial Velocities

See posters 23 (Curtis), 77 (Beatty), 95 (Torres) for exoplanet, BD, and EB results.
2.5 Gyr Sample: Rotation for Ruprecht 147 and NGC 6819

Periods from Meibom et al. (2015)

Curtis et al., in prep
2.5 Gyr Sample: Rotation for Ruprecht 147 and NGC 6819

**NGC 6819**

Rotation Period (d)

Effective Temperature (K)

Periods from Meibom et al. (2015)

**NGC 6819 & Ruprecht 147**

Rotation Period (d)

Effective Temperature (K)

Flat at ~22 days

Curtis et al., in prep
2.5 Gyr Sample: Rotation for Ruprecht 147 and NGC 6819

NGC 6819

Periods from Meibom et al. (2015)

Flat at ~22 days

Are these two rapid outliers?

NGC 6819 & Ruprecht 147

Curtis et al., in prep
Building a Stalled Spin-Down Gyrochronology Model with K dwarf Rotators in Ruprecht 147

Pleiades initial condition:
Rossby = 0.3

NGC 6819 & Ruprecht 147: old-age constraint for model

Data from Rebull et al. (2016) (Praesepe in gray for reference)
1 Gyr: NGC 6811 – my extended sample

“Skumanich” Projection of Praesepe

My Stalled Braking Model

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1.4 Gyr: NGC 752

"Skumanich" Projection of Praesepe

My Stalled Braking Model

“If gyrochronology needs re-tuning, how do I interpret my rotating star?”

Compare directly to the cluster benchmark sample.

(1) age-dating a nearby stellar stream

(2) the *Kepler* intermediate period gap
(1) Is the Nearby Pisces–Eridanus Stellar Stream 1 Gyr Old?

Discovered with Gaia by Meingast et al. (2019):
Only ~130 pc from Earth
Spans 400 pc in length
Stretches 120° across the sky
TESS Reveals that the Nearby Pisces–Eridanus Stellar Stream is only 125 Myr Old

Jason L. Curtis, Marcel A. Agüeros, Eric E. Mamajek, Jason T. Wright, and Jeffrey D. Cummings
Submitted to AJ
(2) What’s up with the *Kepler* intermediate period gap?

Periods from McQuillan et al. (2014).
See also discussions by Davenport et al. (2017, 2018); Reinhold et al. (2019)
Convective turnover time for Rossby from Cranmer & Saar (2011)
Older clusters cross the gap:
It cannot be caused by an event in time (star formation)
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Older clusters cross the gap:
It cannot be caused by an event in time (star formation)
Stellar rotation remains a flawed, but promising clock

- 2.7 Gyr Ruprecht 147 (Curtis, in prep)
- 2.5 Gyr NGC 6819 (Meibom et al. 2015)
- 1.4 Gyr NGC 752 (Agüeros et al. 2018)
- 1 Gyr NGC 6811 (Curtis et al. 2019)
- 670 Myr Praesepe (Douglas et al. 2017)
- 125 Myr Pleiades (Rebull et al. 2016)