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Testing the Stellar Rotation vs. Age Paradigm
Using Wide Binaries in the Kepler & K2 Fields

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https://subarutelescope.org/Pressrelease/2015/05/11/index.html
Gyrochronology

Fast Rotators (young)

Slow Rotators (old)

Animation courtesy of Courtney Epstein (see Epstein & Pinsonneault 2012)
Gyrochronology

Barnes 2007 models
Pizzolato et al. 2003 data

\[ \log(t) = \frac{1}{n} \{ \log(P) - \log(a) - b \times \log(B - V - 0.4) \} \]

NGC 6819 (~2.5 Gyr)
Meibom et al. 2015

\[ \alpha \text{Cen} \ A/B, \ 4.4 \pm 0.5 \text{Gyr} \]
\[ \xi \text{Boo} \ A/B, \ 226 \pm 18 \text{Myr} \]
\[ 61 \text{Cyg} \ A/B, \ 2.0 \pm 0.2 \text{Gyr} \]

Barnes 2007
Gyrochronology, cont.

The Sun 4.6 Gyr
NGC 6819 2.5 Gyr
NGC 6811 1 Gyr
The Hyades 0.6 Gyr

Rotation period (d)

Age (Gyr)

(B - V)\textsubscript{0} photometric colour index (mag)

Meibom et al. 2015
(proxy for mass)
“Fragile” Binaries: Definition

...small galactic clusters containing stars of the same age and composition.” – Greenstein 1986

SLoWPoKES Catalog
http://slowpokes.vanderbilt.edu

Washington Double Star Catalog
http://ad.usno.navy.mil/wds/

Giclas et al. 1971-8

Luyten 1969 et seq.
Fragile Binaries in the Kepler Field (Janes 2017)

93 – 37 = 56 pairs w/ modulation in both stars & B-V colors estimated from:

\[ B-V = a + b (g-K) + c (g-K)^2 \]

22 “best” pairs with B-V > 0.6 colors and P_{rot} > 5 d

Barnes 2010 ages

No correlation
Fragile Binaries in Kepler Field (Godoy-Rivera & Chaname 2018)

17 pairs total
15 pairs vetted by Gaia
2 pairs w/UACA4 data
-3 pairs w/evolved stars

7/14 = 50% "consistent" age slopes

(Angus+15 ages)
Why such poor agreement with gyrochronology?

1. Some may be nonphysical pairs

2. Many components near B-V ~ 0.5 degeneracy in gyrochrones

3. Few B-V values available; estimated B-V values are poor ($\sigma = \pm 0.12!$)

4. Unresolved tertiary components can affect colors and/or rotation rate

5. Unrecognized evolved components do not follow dwarf gyro paradigm

6. Periods may be incorrect

7. Scatter due to differential rotation, multiple spots and/or cycles

8. Current models may not yet be fully mature—which are best?

Use the Janes (2017) Kepler sample of 93 binaries to assess the above
Does the Kepler sample contain any non-physical pairs?

**KIC proper motions**

PM2(Dec) = 0.9994 PM1(Dec) + 0.3465
R² = 0.9979

PM2(RA) = 0.9897 PM1(RA) + 1.1288
R² = 0.9952
Barnes 2018 says 70% of his M67 sample are “double dippers” (see Basri & Nguyen 2018). General agreement suggests differential rotation & cycles don’t impose more than ~10% scatter.
Vetting the Kepler pairs with Zacharias+15 URAT1 griz data

\[ \text{RPM}(m) = m + 5 \log \mu + 5 \]
Vetting Fragile Binaries in the Kepler Field
(data from Janes 2017; Angus+2015 models)

71 Pairs w/ modulation & “real” B-V colors
Vetted by RPM, CPM, colors
- 41 (58%) outside 0.5 < B-V < 1.5
- 15 (21%) w/ discordant ages

15/30 vetted = 50% “consistent” age slopes
Which models are best (subjectively)?

- **Barnes_07 gyrochrones transformed to Jester+05 (g-r)**
  - 86 pairs
  - 24 deleted

- **Angus+15 Gyrochrones transformed to Jester+05 (g-r)**
  - 86 pairs
  - 32 deleted

- **Barnes18 gyrochrones transformed to Jester+05 (g-r)**
  - 86 pairs
  - 20 deleted
Which models are best (objectively)?

\[ y = 1.2319x + 0.2885 \quad R^2 = 0.95579 \]

\[ y = 1.2772x + 0.2756 \quad R^2 = 0.92755 \]

\[ y = 0.9571x + 0.0364 \quad R^2 = 0.99809 \]

\[ y = 0.9953x - 0.07 \quad R^2 = 0.99675 \]

\[ y = 1.1793x + 0.3121 \quad R^2 = 0.95437 \]

\[ y = 1.2764x + 0.1956 \quad R^2 = 0.93222 \]

\[ y = -0.0986x + 2.5883 \quad R^2 = 0.00631 \]

\[ y = -0.1858x + 1.9245 \quad R^2 = 0.0248 \]

\[ y = -0.112x + 2.5295 \quad R^2 = 0.00752 \]
1477 Binaries in the K2 Fields
Dhital+15; Davenport+17; Otani+17-8
Fragile Binaries in the K2 C5, C6, C7, C12 Fields

~340 pairs; 99 w/ rotational modulation in at least one component  BUT
Only 25 pairs w/ rotational modulation in both components and B-V data

Angus+15 Ages for K2 Pairs

-7 (28%) outside 0.5 < B-V < 1.5
-3 (12%) w/ discordant ages
15/18 vetted = 83% agree w/ models
(Janes: 15/30 = 50%)

See Engle & Guinan 2018
Vetted Fragile Binaries in the K2 C5, C6, C7, C12 Fields
Angus+15 models

Consistent proper motions
B-V, g-r, r-i colors from MAST archive
No evolved components (checked via colors & RPM diagram)
No color index anomalies (i.e. unresolved tertiary components)
Expect a “young” sample due to K2 time window of ~80 days
Yield: 18 “vetted” pairs with 0.5 < B-V < 1.5
15/18 = 83% with consistent ages

**Graphs:**
- **K2 Fields Binaries - Angus+15 Ages**
  - \( <\text{dev}> \) from LSQ fit = ± 0.29 Gyr (22%)
  - \( y = 0.8682x + 0.0651 \)
  - \( R^2 = 0.86749 \)
- **K2 Fields Binaries - Angus+15 Ages**
  - \( <\text{age}> = 1.30 ± 0.21 \) Gyr
  - Blue - binary component ages
  - Red - single component ages
Vetted Fragile Binaries in the K2 C5, C6, C7, C12 Fields
Barnes18 models

Consistent proper motions
B-V, g-r, r-i colors from MAST archive
No evolved components (checked via colors & RPM diagram)
No color index anomalies (i.e. unresolved tertiary components)
Expect a “young” sample due to K2 time window of ~80 days
Yield: 18 “vetted” pairs with 0.5 < B-V < 1.5
12/18 = 67% with consistent ages

K2 Fields Binaries - Barnes18 Ages

y = 0.6504x + 0.5117
R² = 0.36079

<dev> from LSQ fit = ± 0.54 Gyr (44%)

<age> = 1.24 ± 0.78 Gyr

Blue - binary component ages
Red - single component ages
CONCLUSIONS

1. The Janes (2017) Kepler binary sample has provided very useful insight on how such pairs can be used to test gyrochronology theory.

2. It is very important to fully vet any prospective sample of binaries; many stars are outside the color/temperature/mass range where gyrochronology applies.

3. If the K2 yield of the 4 fields searched so far (25/340 ≈ 7%) is typical, the remaining 16 fields, which contain >3300 pairs, should yield ~250 vetted pairs.

4. The current work on the K2 sample suggests that carefully vetted samples of binaries can achieve ~20% precision in age estimates.

5. All the dispersion seen in the plots of secondary vs. primary ages cannot be resolved by the approaches described here: current models may need to incorporate additional variables in the period-age-mass relation.

Gaia and TESS will be hugely helpful in all the above efforts!

TBD (on the observational side):

1. Rotation periods drift with spot evolution (differential rotation, latitude, size, number, cycle) – need extended ground-based and/or TESS data.

2. Spectra needed for RV, [Fe/H], etc.
Thank you for listening!
Questions?

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