something about age

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Exoplanet Interests Notwithstanding, we still don’t have the Formation and Evolution of our Solar System Understood.

Compared to planet atmosphere models, saturn is too warm and uranus is too cool.
Non-Self-Luminous Gas Balls Contract then Stabilize, But Fade/Cool Forever as they Age

Burrows et al. (1997)
Even if You Have a Spectrum and Can Estimate Temperature, You Need to Know the Age in Order to Estimate Mass

Burrows et al. (2004)
Fig. 3.— Ages and spectral types of the 23 main-sequence stars with debris disks resolved in scattered light. The five stars hosting the disks presented here (marked in red) are young (< 40 Myr) and have near-solar spectral types (G2-F3) because of sample biases in the NICMOS surveys from which the images originated.

Soummber et al. (2014)
How do Debris Disks Evolve?

Chen et al. (2014)
How Old is that Star with a Faint Companion Next to It?

Fig. 2.— The calculation of an age probability distribution for a target, HIP 107350, without a reliable moving group age. HIP 107350 has an exceptional array of secondary age indicators, which enable a good constraint on its age. Most other stars without kinematic ages have much broader posterior probability distributions.

Brandt et al. (2014a)
Are those Faint Objects Planets or Brown Dwarfs?
What is the Distribution of Planet and Brown Dwarf Companions as a Function of their Mass and Separation?

Brandt et al. (2014b)
Assumption:

Disk/Planet Age $==$ Star Age
But there is No **Fundamental**
Diagnostic of Stellar Age

We are stuck with:

- **Model predictions**
  - isochrones / evolution
  - lithium / depletion
  - asteroseismology (i.e. pulsations)

- **Empirical calibrations**
  - rotation / spindown
  - activity / decline
  - lithium / depletion
  - metallicity / increase

- **Association with other stars/cluster of “known” age**

* e.g. based on nuclear physics or gravity, though g-mode pulsation comes close
Valuable References

• Soderblom, Hillenbrand, Jeffries, Mamajek, Naylor 2014

• Jeffries, 2014
  USING ROTATION, MAGNETIC ACTIVITY AND LITHIUM TO ESTIMATE THE AGES OF LOW MASS STARS

• Soderblom, 2010

• Mamajek, Soderblom, Wyse (eds.)
  THE AGES OF STARS, IAUS 258
Age from Stellar Evolution Models

• Can try to catch stars in pre-main sequence (younger system means brighter planet), but still significant uncertainties in theoretical isochrones.

• Near, on, or barely post-main sequence stars have imprecise isochronal ages due to isochrone crowding and systematic effects due to metallicity.

• Evolved stars have okay isochronal ages, but too old for directly imaging planets. B/A stars are the exception, due to their rapid evolution (though require higher contrast to reach same mass planet).
Pre-Main Sequence Isochrones

$L \propto t^{-2/3}$

$\sigma(\log t) = 1.5 \sigma(\log L)$
Main Sequence Lifetimes

Bluest (B−V) on Main Sequence
Lejeune+(2001) Z=0.02 tracks

knee in planet cooling curves

E. Mamajek (CfA)
Higher Mass Stars Evolve Away from MS Before Lower Mass Stars Reach it
Flowchart for Young Star HR Diagram

- **SED or colors**
  - Spectral type (or temperature)
  - Possibly info on disk/accretion from database, including errors

- Can influence colors/spectrum. Also causes variability over time. These are nuisances to be dealt with judiciously.

- **SpT → stellar temperature = f (spectral class, luminosity class)**
  - Intrinsic colors = f (temperature, gravity)
  - Reddening law / Extinction = f (wavelength, grain properties)

  - from carefully chosen lookup tables

- **log L/L\(_{\text{sun}}\)**

  - **A\(_{\text{V}}\)**

  - **distance** from database

- **log L/L\(_{\text{sun}}\)** + log Teff from above

  - **R/R\(_{\text{sun}}\)**

  - pre-main sequence evolutionary tracks and isochrones from theory

  - Can be straight interpolation or bayesian probability distribution

- **M/M\(_{\text{sun}}\) and age/Myr**

  - observational errors

  - systematic differences among various calibration scales

  - accumulated error in observations, variability, accretion effects, calibration systematics, and uncertain distance

  - differences in track physics leads to systematic difference in mass/age results
Young Star Clusters of Interest

<1 Myr old

100 Myr old
Observed scatter in $\log L/L_\odot$ diminishes from $\sim 0.5$ dex at 1 Myr to $\sim 0.15$ dex at $>10$ Myr, consistent with estimated empirical uncertainties.
Don’t Forget about Gravity (It’s the Law)

Herczeg & Hillenbrand (2014)
Lithium Depletion Theory

Li burns at $T = 3 \times 10^6 \text{K}$ and does so rapidly when material reaches that $T(r)$ via convection.

Figure 1. H-R diagram showing Behrend & Maeder (2001) pre-main sequence evolutionary tracks for stellar masses up to $4 M_\odot$. The dashed blue line marks the position of the birthline. All stars with masses less than $3.5 M_\odot$ will undergo a stage along their pre-main sequence evolution in which they have either partially or fully convective interiors. A star with a mass of $1.5 M_\odot$ or more will be subject to several fundamental changes in their internal structure, having a fully convective interior near the birthline, to developing a radiative core, to becoming fully radiative and finally developing a convective core just before reaching the Zero Age Main Sequence (black dot-dashed line).
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Fig. 3. Locus in the HR diagram corresponding to the Li burning. The red segment shows the maximum burning.
HR Diagram vs Lithium Ages for Clusters

compiled in Soderblom et al. (2014)

Fig. 2. A comparison of cluster LDB ages with ages determined from the upper-main-sequence (UMS) and main-sequence turn-off (MSTO) using models without core convective overshoot and with a moderate amount of core overshoot (about 0.2 pressure scale heights). Data and sources are from Table 1.

**TABLE 1.** LDB ages compared with ages determined from upper-main-sequence fitting using models both with and without convective overshoot.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>I&lt;sub&gt;LDB&lt;/sub&gt; (mag)</th>
<th>LDB Age (m.y.)</th>
<th>Ref.</th>
<th>M&lt;sub&gt;bol&lt;/sub&gt; (mag)</th>
<th>Homogeneous LDB Age (m.y.)</th>
<th>Mermilliod MS Age (m.y.)</th>
<th>Overshoot MS Age (m.y.)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>β Pic MG</td>
<td>18.95 ± 0.30</td>
<td>21 ± 4</td>
<td>[1]</td>
<td>8.28 ± 0.54</td>
<td>20.3 ± 3.4 ± 1.7</td>
<td>&lt;20</td>
<td>26.3±3.3 ± 1.3</td>
<td>[2]</td>
</tr>
<tr>
<td>NGC 1960</td>
<td>16.64 ± 0.10</td>
<td>22 ± 4</td>
<td>[3]</td>
<td>8.57 ± 0.33</td>
<td>23.2 ± 3.3 ± 1.9</td>
<td>36 ± 5</td>
<td>41 ± 12 ± 1.9</td>
<td>[11]</td>
</tr>
<tr>
<td>IC 4665</td>
<td>16.54 ± 0.14</td>
<td>28 ± 5</td>
<td>[4]</td>
<td>8.78 ± 0.34</td>
<td>25.4 ± 3.8 ± 1.9</td>
<td>36 ± 5</td>
<td>41 ± 12 ± 1.9</td>
<td>[12]</td>
</tr>
<tr>
<td>NGC 2547</td>
<td>15.64 ± 0.08</td>
<td>35 ± 3</td>
<td>[5]</td>
<td>9.58 ± 0.20</td>
<td>35.4 ± 3.3 ± 2.2</td>
<td>41 ± 12 ± 1.9</td>
<td>41 ± 12 ± 1.9</td>
<td>[13]</td>
</tr>
<tr>
<td>IC 2602</td>
<td>16.21 ± 0.07</td>
<td>46*6-5</td>
<td>[6]</td>
<td>9.88 ± 0.17</td>
<td>40.0 ± 3.7 ± 2.5</td>
<td>36 ± 5</td>
<td>41 ± 12 ± 1.9</td>
<td>[13]</td>
</tr>
<tr>
<td>IC 2391</td>
<td>17.70 ± 0.15</td>
<td>50 ± 5</td>
<td>[7]</td>
<td>10.31 ± 0.16</td>
<td>48.6 ± 4.3 ± 3.0</td>
<td>36 ± 5</td>
<td>45 ± 5 ± 1.9</td>
<td>[14]</td>
</tr>
<tr>
<td>a Per</td>
<td>17.86 ± 0.10</td>
<td>90 ± 10</td>
<td>[8]</td>
<td>11.27 ± 0.21</td>
<td>80 ± 11 ± 4</td>
<td>51 ± 7</td>
<td>80 ± 11 ± 4</td>
<td>[15]</td>
</tr>
<tr>
<td>Pleiades</td>
<td>17.86 ± 0.10</td>
<td>125 ± 8</td>
<td>[9]</td>
<td>12.01 ± 0.16</td>
<td>126 ± 16 ± 4</td>
<td>78 ± 9</td>
<td>120 ± 11 ± 4</td>
<td>[15]</td>
</tr>
<tr>
<td>Blanco 1</td>
<td>18.78 ± 0.24</td>
<td>132 ± 24</td>
<td>[10]</td>
<td>12.01 ± 0.29</td>
<td>126 ± 23 ± 4</td>
<td>115 ± 16 ± 16</td>
<td>[10]</td>
<td></td>
</tr>
</tbody>
</table>
Seismology Theory in a Single Slide

Small separations determined by core conditions (and hence age in MS stars)

Large separation, determined by mean density

\[ \Delta \nu_0 = \left( 2 \int_0^R \frac{dr}{c} \right)^{-1} \]

\[ c_s^2 = \frac{\gamma P}{\rho} \]

⇒ "p-mode"

simulation by Sarbarni Basu
Pre-Main Sequence Stellar Pulsation

- Higher-mass pre-ms evolutionary tracks cross the classical instability strip in the δ-Scuti region (kappa mechanism)
- Lower-mass stars very early in pre-ms evolution may cross a deuterium-burning instability strip (epsilon mechanism)
- Pulsations predicted on a dynamical timescale -- few hours
Main and Post-Main Sequence Stellar Pulsation

Typical power spectrum of sun-like oscillations

\[ \Delta \nu_0 = \left( 2 \int_0^R \frac{dr}{c} \right)^{-1} \]

\[ c_s^2 = \frac{\gamma P}{\rho} \]

<table>
<thead>
<tr>
<th>HD49933 (^{(1)})</th>
<th>Sun (^{(2)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ((M_\odot))</td>
<td>1.12 ± 0.03</td>
</tr>
<tr>
<td>Age ((\text{Gyr}))</td>
<td>2.9 ± 0.4</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Creevey & Bazot, 2011
\(^{(2)}\) Metcalfe, Creevey & Christensen-Dalsgaard, 2009

abundances matter!

R-3%, M-9%, A-20-40%
+ Systematics

Chaplin et al. Incl. Creevey 2013

Logg < 0.02 dex

Creevey, Thevenin et al. 2013
Remember, there is No **Fundamental** Diagnostic of Stellar Age

We are stuck with:

- Model predictions
  - isochrones / evolution
  - lithium / depletion
  - asteroseismology (i.e. pulsations)

- Empirical calibrations
  - rotation / spindown
  - activity / decline
  - lithium / depletion
  - metallicity / increase

- Association with other stars/cluster of “known” age
  
  * e.g. based on nuclear physics or gravity, though g-mode pulsation comes close
Now The Empirical Big Three

- Rotation
- Activity
- Lithium
Even the Old Sun is “Active”
“Activity” is Driven by Stellar Rotation – Stars Spin-up as Contract in Pre-MS then when reach MS start to spin-down
While the rotation medians are well-behaved, the data actually show lots of scatter prior to (mass-dependent) convergence!

Fig. 1. Rotation rates/periods for sets of solar-type stars in coeval clusters as a function of age (adapted from Gallet & Bouvier 2013). The PMS, ZAMS and MS phases are marked and the dominant physical processes at work are indicated. Beyond ages of \( \sim 0.5 \) Gyr rotation rates converge for stars of a solar mass, or at least are predicted to converge, to a close-to-unique function of age. This convergence takes longer at lower masses.
The issue is a tail of rapid rotators, the percentage of which declines as a function of cluster age.

**Fig. 15.** Period versus mass distributions for clusters with an age ranging from 4 to 150 Myr. The clusters’ name and age are given in each panel. Red dotted lines are drawn at periods of 0.2 and 10 days to guide the eye. References: Cep OB3b: Littlefair et al. (2010); NGC 2362: Irwin et al. (2008a); NGC 2547: Irwin et al. (2008b); Pleiades: Hartman et al. (2010); M 50: Irwin et al. (2009); NGC 2516: Irwin et al. (2007b); M35: Meibom et al. (2009).
The issue is a tail of rapid rotators, the percentage of which declines as a function of cluster age.

**Fig. 2.** A schematic of the location of the I- and C-sequences in the rotation period, colour plane. The I-sequences (gyrochrones) were calculated according to the formula advocated by Barnes (2007), the C-sequences from the formula given by Barnes (2003). The Sun and two illustrative stars (A and B) are shown and discussed in the text.
$P = f(B-V) \cdot g(t_{\text{Myr}})$

$f = 0.518(B-V - 0.508)^{0.302}$

$g = (t_{\text{Myr}})^{0.625}$

fit good to 0.06 dex in age
Young Star Chromospheric Activity

Fractional luminosity in Ca II emission cores at 3933 and 3968 Å decreases with stellar age as should UV continuum.
Quantifying Chromospheric Emission - Lines

Gymnastics with indices plus color calibration $\rightarrow R'_{\text{HK}}$

Wright et al. (2004)
Fig. 4. The age-dependence of the chromospheric $R'_{\text{HK}}$ index. The data are taken from Mamajek & Hillenbrand (2008). Solid points are clusters with HK measurements on the Mt Wilson system. The horizontal bars represent the rms dispersion. Open symbols are several clusters with data recalibrated onto the Mt Wilson system (see Mamajek & Hillenbrand for details); the Sun is also shown. Various age-activity relations proposed in the literature are shown. The Mamajek & Hillenbrand curve was defined using the plotted data. Note the large dispersion in $R'_{\text{HK}}$ at ages $\leq 200$ Myr, presumably caused by a large spread in rotation rates.
Activity in Low Mass Stars - Hα

[Kruse et al. 2009]
Quantifying Chromospheric Emission - Continuum

Shkolnik & Barman (2014)
UV Excess ➔ Activity ➔ Age

• Measured UV excess = continuum + line (LyA, Mg II, etc.).

• Line emission comprises ~60% of FUV and ~40% of NUV and, in addition to the chromospheric component, some of this is coronal and transition region emission [Pagano 2009].

• For solar-type field stars near to the sun, the FUV excess is correlated with the optical chromospheric line index $R'_{\text{HK}}$ ($\pm 0.2$ dex scatter) [Findeisen, Hillenbrand, Soderblom 2011; Smith & Redenbaugh 2010], which is then correlated to stellar age [Mamajek & Hillenbrand 2008].

• UV excess is also correlated directly to stellar age, but statistically very poor ($\pm 0.4$ dex scatter).
When both FUV and NUV can be detected, the former is a better discriminant of stellar activity. Note wide scatter!

UV − V vs. $R'_{HK}$ diagrams of our volume-limited Hipparcos sample. In the left panel, red points have $B − V > 0.8$, green points have $0.65 < B − V < 0.8$, and blue points have $B − V < 0.65$. In the right panel, red points have $B − V > 0.9$, green points have $0.8 < B − V < 0.9$, and blue points have $B − V < 0.8$. The ellipses at the top of either panel show the median errors in color. The utility of the UV as an activity indicator can be seen directly as a downward trend in UV − V color with increasing activity. We plot Equations (2) and (4) at the median B-V of each bin.
However, GalEx quickly loses FUV sensitivity towards lower masses, older ages, larger distances. Further, many FUV-detected stars are saturated at NUV.

UV – J vs. J – K diagrams of our cluster and moving group sample. Each symbol corresponds to a different association, as shown in the legend, while the hue maps linearly to log age. The ellipses at the upper left of either figure show the median errors in color. The NUV panel shows a clear trend with age, but any relation between FUV and age is obscured by non-detections.
Our Old Inactive Sun

Hotter coronal activity on larger scale than cooler chromospheric activity.
circles (filled and open) = chromosphere via H&K
squares (red) = corona via x-rays

Sanz-Forcada (2013)
Young Star Coronal Activity

Fig. 3. The age-dependence of coronal X-ray luminosity for stars of about a solar mass. The median $L_x$ for clusters are shown with squares; the error bars indicate the interquartile range. Open circles are measurements of field stars with estimated ages. Lines connect observations of the same star at different epochs. The solid line indicates the locus where $L_x/L_{bol} = 10^{-3}$ (from the models of Siess, Dufour & Forestini 2000), which is the observed saturation threshold for X-ray activity.

Jeffries (2014)
Another Clock: Lithium Depletion

Li I absorption at 6707 Å decreases with stellar age.
Fig. 6. Empirical Li depletion patterns for a set of fiducial clusters in the form of equivalent width of the 6708Å features vs (dereddened) colour. Data are from Soderblom et al. (1993); Jones et al. (1996); Randich et al. (1997, 2001); Sergison et al. (2013); Jeffries et al. (2014).
Age Estimation Techniques (Myr to Gyr)

- HR diagram / isochrones
- Asteroseismology
- Rotation
- Activity:
  - $R'_{HK}$ (Ca II index)
  - Halpha
  - soft xray
- Lithium abundance
- Statistics of Age-[Fe/H]
- Kinematics and Age-$\sigma_v$
- Open Cluster membership

[Hillenbrand et al. 2009 CS XV]
How Well Can we Do?

For field stars, the dispersion in ages derived using these different techniques is 0.2-0.35 dex, meaning that for stars younger than the Sun we know ages to only 50-150 %

[Hillenbrand et al. 2009 CS XV]
Jeffries (2014)
Synopsis

Soderblom et al. (2014) PPVI

<table>
<thead>
<tr>
<th>Age Range</th>
<th>&lt;1-10 Myr</th>
<th>~10-100 Myr</th>
<th>&gt;100 Myr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Range</td>
<td>PMS isochrones, gravity, Rsini, seismology?</td>
<td>LDB, PMS isochrones, gravity lithium, gravity</td>
<td>LDB, PMS isochrones rotation/activity</td>
</tr>
<tr>
<td>&lt;0.1 $M_\odot$</td>
<td></td>
<td>lithium, R-C?</td>
<td>rotation/activity</td>
</tr>
<tr>
<td>0.1-0.5 $M_\odot$</td>
<td>PMS isochrones, gravity, lithium, Rsini</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5-2.0 $M_\odot$</td>
<td>PMS isochrones</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;2.0 $M_\odot$</td>
<td>PMS isochrones, MS isochrones, seismology, R-C</td>
<td>MS isochrones, seismology</td>
<td>MS isochrones</td>
</tr>
</tbody>
</table>

Young stars / many methods:

Brandt et al. (2014a)

Old stars / isochrones:

Soderblom (2010) ARAA from Takeda et al. (2007)
Valuable References

• Soderblom, Hillenbrand, Jeffries, Mamajek, Naylor 2014

• Jeffries, 2014

• Soderblom, 2010

• Mamajek, Soderblom, Wyse (eds.)
  THE AGES OF STARS, IAUS 258
What About The Early Type Stars with Directly Imaged Companions?

Isochrones provide the best quantitative age estimates for intermediate mass field stars.

Application in observational (e.g. color-magnitude) space or physical parameter (log T, log L, log g) space.

HR diagram: requires precise atmospheric parameters.

Accuracy of uvbyβ photometry relative to fundamental methods:
- ~0.2 dex in log g
- ~2% in $T_{\text{eff}}$

*tracks from Bressan et al. (2012)*
Early Type Ages: Effect of Rotation

\[ \Delta T_{\text{eff}} \propto (v \sin i)^2 \]
\[ \Delta \log g \propto (v \sin i)^2 \]

100% increase in inferred age not uncommon!

tracks from Bressan et al. (2012)

vectors based on vsin(i) corrections of Figueras & Blasi (1998)
Early Type Ages Example

Kappa And

\[ T_{\text{eff}} = 11361 \pm 66 \text{ K} \]
\[ \log g = 4.10 \pm 0.03 \text{ dex} \]
(Fitzpatrick & Massa 2005)

\[ \tau = 220 \pm 100 \text{ Myr} \]
(Hinkley et al. 2013)

Our median age and 68% confidence limits:
\[ \tau = 189 \pm^{14}_{13} \text{ Myr} \]
95% confidence limits:
\[ \tau = 189 \pm^{24}_{31} \text{ Myr} \]

Trevor David & Hillenbrand (2015)
Early Type Ages Example

Taking rotation into account (v sin i = 176 km/s)

\[ T_{\text{eff}} = 11361 \pm 66 \text{ K} \]
\[ \log g = 4.10 \pm 0.03 \text{ dex} \]

(Fitzpatrick & Massa 2005)

\( \tau = 220 \pm 100 \text{ Myr} \)
(Hinkley et al. 2013)

68%: \( \tau = 101 \pm ^{18}_{18} \text{ Myr} \)
95%: \( \tau = 101 \pm ^{32}_{37} \text{ Myr} \)

Trevor David & Hillenbrand (2015)