The Ages of Young Stars

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Aims and Scope

For young stars up to the age of \textbf{\~100 Myr}:

- Can we categorise stars?
- Can we put them in age order?
- Can we estimate age ratios or age differences?
- Can we estimate absolute ages?
# A hierarchy of methods

<table>
<thead>
<tr>
<th><strong>Fundamental</strong></th>
<th>None available</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Semi-Fundamental</strong></td>
<td>Lithium Depletion Boundary</td>
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<tr>
<td></td>
<td>Kinematic Traceback</td>
</tr>
<tr>
<td><strong>Model-Dependent</strong></td>
<td>Isochrone fitting, Asteroseismology</td>
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<tr>
<td></td>
<td>Surface gravity, Radii, Radiative-convective gap</td>
</tr>
<tr>
<td><strong>Empirical</strong></td>
<td>Rotation, activity, disks, lithium</td>
</tr>
<tr>
<td><strong>Statistical</strong></td>
<td>Metallicity, Kinematics - not useful</td>
</tr>
</tbody>
</table>
The Lithium Depletion Boundary

In low mass stars <0.4 $M_{\odot}$

Fully convective

Li burns at $T_C = 3 \times 10^6$ K

When core reaches $T_C$, Li is rapidly burned.

Little dependence on convection treatment, nuclear rate, opacities; some dependence on atmosphere, equation of state.

LDB - the luminosity at which Li remains unburned
The Lithium Depletion Boundary

In low mass stars <0.4 M☉

- Fully convective
- Li burns at $T_c = 3 \times 10^6$ K

When core reaches $T_c$, Li is **rapidly** burned.

**Little dependence** on convection treatment, nuclear rate, opacities; **some dependence** on atmosphere, equation of state.

LDB - the luminosity at which Li remains unburned
$L_{\text{bol}}$ when depletion occurs is model insensitive (20-200 Myr)

$T_{\text{eff}}$ when depletion occurs is atmosphere dependent
Insensitive to measurement uncertainties – distance, extinction etc.

Requires good spectroscopy and photometry of faint stars

Difficult to locate LDB – binarity, variability, age spreads?

8 CLUSTERS HAVE MEASURED LDB

22-132 Myr

Kinematic Ages

“Traceback Ages” – tracing orbits of group members to a past minimum dispersion/size.

“Expansion Ages” – measuring velocity vs. position trends
(age = 1/slope)

“Flyby Ages” – time of min. separation between star-group, group-group (star/group from same cloud?)

“Runaway Ages” – flyby age where either a binary-supernova or dynamical ejection likely occurred.

- Conceptually simple, though require excellent astrometry,
- But these techniques have checkered histories.

Hoogerwerf et al. 2001 A&A 365, 49
Soderblom 2010 ARA&A 48, 581
Traceback Ages

- Famous example: Beta Pic Moving Group
- Using Hipparcos astrometry and published radial velocities, 3 subsequent studies estimate traceback age of $\sim 11-12$ Myr.

Song et al. 2003 ApJ 599, 342
• But... results hinge on inclusion/exclusion of particular stars.

• Using revised Hipparcos astrometry, the group is *not* smaller in the past

• Expansion rate inconsistent with 12 Myr at >3σ

Mamajek, in prep. (using van Leeuwen’s revised Hipparcos astrometry)
Ages from the UMS

Log $L/L_\odot$

M$_V$

Requires a distance!
Physical uncertainties in high mass isochrones

1. Rotation
2. Overshooting

Both increase main sequence lifetimes

Introducing rotation or overshoot increases estimated ages from MSTO

Upper M-S fitting

NGC 6530 0.25 Myr
(Geneva-Bessell)

$Pr(\tau^2)=0.03$

A poor fit to the ZAMS
NGC 6530 \( 5.50 \pm 0.6 \) Myr

(Geneva-Bessell)

\[ Pr(\tau^2) = 0.67 \]

A much better fit achieved allowing the age to go free
LDB vs UMS comparison

The graph compares the LDB ages with the UMS/MSTO ages, showing data points for both 'No overshoot' and 'Moderate overshoot' scenarios. The data points are scattered along the x-axis representing LDB age and the y-axis representing UMS/MSTO age (in Myr). The graph includes error bars for each data point, indicating the variability in the measurements.
Ages from the PMS

\[ L \propto t^{-2/3} \]
**Age from the PMS?**

1. Extinction
2. Accretion
3. Age Spread?
4. Variability
5. Binarity

All contribute to the scatter

\[ \sigma(\log t) = 1.5 \sigma(\log L) \]

Siess isochrones

\[ \sigma(\log L) = 0.3 \text{ dex} \]

Are these spreads in luminosity real? If so, do they imply large age spreads?


Estimated uncertainties
From Reggiani et al. 2011

<table>
<thead>
<tr>
<th></th>
<th>σ(log L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variability</td>
<td>0.030</td>
</tr>
<tr>
<td>Distance</td>
<td>0.015</td>
</tr>
<tr>
<td>Extinction</td>
<td>0.050</td>
</tr>
<tr>
<td>Accretion</td>
<td>0.070</td>
</tr>
<tr>
<td>Binarity</td>
<td>0.016</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.10</td>
</tr>
</tbody>
</table>

(More typically 0.15 dex)

\[ t \propto L^{-3/2} \text{ so } \sigma(\log t) = 0.15-0.2 \text{ dex} \]

\[ \sigma(\log t) < \sigma(\log \text{age}) \] - Uncertainties cannot explain spread

(Unless they have been badly underestimated)  Reggiani et al. 2011, A&A, 534, A83
Astrophysical scatter in logL diminishes at age > 10 Myr to ~0.15 dex in G/K/early M stars.
Model isochrones do not agree and not in a consistent sense!

Factor of 2 differences at $<10$ Myr, smaller differences at older ages

130 Myr isochrone and BT-Settl atmospheres do not match the Pleiades for $T<4000$K

Reasonable agreement between UMS and PMS ages

Also see
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

Seismology potentially more precise

COROT and MOST monitoring in NGC 2264

Age of this star from HR diagram: 6-10 Myr

Age from seismology: 10-11 Myr

Zwintz et al. 2013, A&A, 552, A68
Gravity diagnostics

- Require a 2-dimensional classification
- Little hope of absolute accuracy
- Capable of providing the rank order of ages and separating them with a resolution of a few Myr at 5-20 Myr
The radiative-convective gap

- Rapid evolution in HRD caused by development of a radiative core.
- Opens up an R-C Gap with an age-dependent width and color <15 Myr.
- Independent of distance and extinction.

Rotation and activity

Gallet & Bouvier 2013, arXiv 1306.2130
Rotation and activity

Age dependent slope in period-mass relation?

Disc presence as an independent clock?


Based on Spitzer data
Lithium depletion – is age dependent

But also depends on convective efficiency, composition, magnetic fields, rotation...

Many uncertainties in the models.

Cannot be used to derive absolute ages

Two convective efficiencies. Isochrones of Li depletion at 20 and 200 Myr.


Fraction of Li left

CB97 models
alpha=1.0
alpha=1.9

Li/Li₀
Empirical Li depletion
The Key Points

Semi-Fundamental Ages

**LDB:** Luminosity at the LDB.
- Works well for 20-200 Myr,
- Gives ages to 10-20%.
- Establishes a set of calibration clusters.

**Kinematics:** Not recommended yet.
- Problems with precision, membership and locating the origin of runaways.
- Gaia will help!
The Key Points

Model-Dependent Ages

**UMS and PMS isochrones** can rank clusters in age order.
- UMS: theoretically robust, but poor precision
- PMS: precise, but factor 2-3 absolute uncertainties and observationally difficult at <10 Myr; better at older ages.
- Age spreads a complicating factor?

**Pulsations, R-C gap, Gravity indicators** – show promise as **distance-independent methods**
The Key Points

Empirical Ages

**Lithium:** sensitive for K/M dwarfs 10-100 Myr
- Factor 2 precision for 1 such star

**Disks/Accretion:** ~50% precision at 1-15 Myr
- But significant hazards – known unknowns!

**Rotation/Activity:** hopeless at 10-100 Myr.
- Possible use for M-stars at 1-10 Myr
Final Thought

DDB ?

LDB

1 Myr

10 Myr

100 Myr

99% D depletion