A Splinter Session on the Thorny Problem of Stellar Ages

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Abstract. Accurate stellar ages remain one of the most poorly constrained, but most desired, astronomical quantities. Here we briefly summarize some recent efforts to improve the stellar age scale from a subset of talks from the “Stellar Ages” splinter session at the 14th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun. The topics discussed include both the apparent successes and alarming discrepancies in using Li depletion to age-date clusters, sources of uncertainty in ages due to input physics in evolutionary models, and recent results from asteroseismology and gyrochronology.

1. Introduction

“What is the age of [star catalog] [index #]?” is probably one of the most frustrating astronomical inquiries that one can make, and also one of the most quixotic of tasks to tackle. For studies of the evolution of interesting properties related to stars (e.g. planetcity, circumstellar disk evolution, etc.), astronomers would ideally like a robust means of estimating the age of any star in the sky. There are difficulties with age estimation throughout the stellar mass spectrum, with some stellar mass and age regimes more amenable to age-dating than others due to rapid structural evolution. To make matters worse for the estimation of ages for field stars, most useful age diagnostics can manifest a wide range of values amongst stars in supposedly coeval clusters. There are age-dating methods that are becoming more precise (e.g. Li depletion boundary, gyrochronology, asteroseismology), but it remains to be seen how accurate they are when some underlying critical physics and parameters (e.g. the solar metal fraction, convection, etc.) are still matters of active debate. Of course, the “golden spike” of the stellar age scale is the Sun, which has its age constrained by lead isotopic ages of the oldest portions of meteorites (the Ca-Al-rich inclusions; 4567.2 $\pm$ 0.6 Myr old; Amelin et al. 2002).

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At the Cool Stars 14 meeting held in Pasadena in 2006, a splinter session of talks was held devoted to discussing contemporary issues regarding the ages of cool stars. Here we summarize a subsample of those talks (which due to time constraints covered only a subsample of age-related topics) and point the reader to recent studies relevant to the stellar age scale. The text in the following sections reflects the current state of the field in the view of the various authors, and no attempt has been made to reconcile their results and opinions.

2. Stellar Ages: How Far Can We Go? (Barrado)

A survey in the literature will easily show that, for a given stellar association, there is a large range of age estimates. These differences arise from different facts. First, we have different sets of theoretical models which might produce different answers for the same dataset. In any case, the comparison between observational properties and those predicted by theory is not an easy task (see Stauffer et al. 1995). Moreover, stars are individuals, and they have properties, such as starspots, accretion rates, initial conditions, etc., which can alter the age estimate. As an example, colors can be modified by surface inhomogeneities (Stauffer et al. 2003) which can affect a cluster's placement in a color-magnitude diagram. An additional problem is coevality. It is normally assumed that members of an association are born almost at the same time, but this is not necessarily true. On the other hand, among the methods we use to estimate ages, both primary (upper Main sequence and isochrone fitting, eclipsing binaries, spectral features, lithium) and secondary (stellar activity, rotation, group membership), there are many pitfalls since there are uncertainties in the input physics. Moreover, each of these methods is valid for a given range of stellar ages and masses, a fact that is not always honored. All these sources of uncertainty make the stellar chronology very uncertain although sometimes we can find formal errors of tenths of Myr, which are far from our present capabilities.

From my point of view, we should aim for consistency. A given property (or properties) allow us to sort a set of stellar associations from the youngest to the oldest, even if we can not derive absolute ages. Even if other properties produce a different age scale, at least we should be able to have the same kind of sequence, with Taurus being younger than the $\lambda$ Ori cluster, which is younger than IC 2391, and still much younger than the Pleiades. Eventually, we should be able to construct different ages scales which should be consistent with each other, and should produce absolute and well as relative ages. This only can be achieved with a considerable effort in the theoretical and observational sides of the problem. Specifically, we should gather very large datasets with the same setup for a large number of stellar association, in order to avoid biases.

3. The Li Depletion Boundary in the $\beta$ Pic Group (Jensen)

Pre–main-sequence (PMS) Li depletion has the potential to be a valuable age indicator for late-type PMS stars, (see e.g., the review by Jeffries 2000). Like any age indicator, however, the models that tie a particular Li abundance and effective temperature ($T_{\text{eff}}$) to an age must be calibrated with empirical data.

We observed twelve late-type members of the $\beta$ Pic moving group (BPMG) at spectral resolution $R = 40,000$ using the echelle spectrograph on the 4-meter
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Figure 1. $T_{\text{eff}}$ vs. Li abundance for stars in the 10–12 Myr-old $\beta$ Pic moving group. For each model, isochrones for 1, 3, 10, 30, and 100 Myr are plotted.

Blanco telescope at CTIO. Spectral types were determined from the TiO band indices, and converted to $T_{\text{eff}}$ using the intermediate scale given by Luhman (1999) for the M stars and the main-sequence (MS) scale from Kenyon & Hartmann (1995) for earlier types. We determined Li abundances by comparing the observed spectra to a grid of high-resolution synthetic spectra.

Fig. 1 shows Li abundance data for the twelve stars overlaid on three sets of models: (D’Antona & Mazzitelli 1997, 1998; Siess et al. 2000; Baraffe et al. 1998). These stars all have ages of $\sim$10–20 Myr based on their HR diagram positions, but the systematic trend observed in their Li depletion is that full depletion of Li occurs much more rapidly for the M stars than the models predict. In each of the models, the right side of the dip in the lithium depletion isochrones, which indicates the lithium depletion boundary (LDB), consistently falls at effective temperatures too high for our data if we assume the HR diagram ages are correct. Three stars with spectral types of M4 show fully-depleted Li, with an upper limit of $\log A(\text{Li}) < -1$; none of the models predicts significant Li depletion in stars of this $T_{\text{eff}}$ until ages $> 30$ Myr.

Some authors have questioned whether the BPMG is truly a coeval group of stars with a common origin. Even if one accepts an age spread in the sample, however, the components of individual binary or multiple systems should be coeval with each other. Examination of the Li abundances in individual systems in the sample shows the same discrepancies as the sample as a whole; the pair BD–17 6128 A/B, and the triple systems HD 155555 A/B/C and GJ 803/799N/799S, are inconsistent with having a single Li-depletion age for all components. The direction of the systematic discrepancies reported here are consistent with previous work showing that the LDB occurs at a cooler $T_{\text{eff}}$ for a given age than the models predict. Our results are also consistent with the work of White & Hillenbrand (2005), who suggest that the M3 classical T Tauri star could be a young member of Tau-Aur despite its large Li depletion.

4. Lithium Depletion Ages and Age Spreads (Randich)

HR diagrams of several young clusters and associations suggest the presence of age spreads among cluster members. Understanding whether these spreads are intrinsic or rather due to errors in the determination of stellar parameters and
misplacement of the stars on the HR diagram, is crucial for gaining insight into the cluster star formation (SF) histories and, in particular, to put constraints on the overall duration of the SF process (Hillenbrand, this volume). Constraints on aspects of SF and early (sub)stellar evolution can also be gathered through the investigation of PMS clusters with ages \( \sim 10\) to 50 Myr. SF in PMS clusters has ceased, implying that their members have attained their final masses and that these clusters do not present the complications that are intrinsic to SF environments. On the other hand, PMS clusters are generally too young to be dynamically relaxed and thus reveal a cleared view of the final product of the SF process. In this context, using the multiplex instrument FLAMES on VLT/UT2, we have obtained medium/high resolution spectra of low-mass members of the Orion Nebula Cluster (ONC), the \( \sigma \) Ori cluster, and the PMS cluster IC 4665 (de Wit et al. 2006). Our main goal was the measurement of their lithium content, which provides an independent clock to derive the ages and age spreads.

**ONC and \( \sigma \) Ori** – (Palla et al. 2005, 2007; Sacco et al. 2007): We have observed 141 high-probability cluster members (membership probability from proper motion \( \geq 90\% \)) down to \( \sim 0.1 \, M_\odot \) in the ONC and 98 cluster candidates in \( \sigma \) Ori. Li abundances were derived from veiling corrected pseudo-equivalent widths (pEWs) of the Li \( \iota \) 670.8 nm feature. Radial velocities were also measured, along with the strength of the He \( 667.8 \) nm (ONC) and H\( \alpha \) (\( \sigma \) Ori) emission lines. All the ONC targets were confirmed as members, while in \( \sigma \) Ori 59 \textit{bona fide} members were identified. Li abundances are consistent with the interstellar value for most of the sample stars in both clusters. However, six stars in the ONC and three stars in \( \sigma \) Ori show Li depletion factors between \( \sim 2\) to 50 (ONC) and \( \geq 100 \) (\( \sigma \) Ori). Nuclear ages and masses for four Li-depleted stars in the ONC and two of the three Li-depleted stars in \( \sigma \) Ori are in excellent agreement with isochronal ages and masses. Inferring ages are in the range \( \sim 10\) to 30 Myr, much older than the bulk of the cluster populations. Hence, for both regions, there is independent evidence for a population of old stars mixed with the much larger assembly of young objects, supporting the suggestion that SF in the two clusters has not occurred in a short single burst, but has rather continued for a long time, much in excess of the dynamical time scale.

**IC 4665** – (Manzi et al. in prep.): With a turn-off age of 36 Myr, this cluster represents a good candidate PMS cluster. We observed 158 candidate members and confirmed membership for 45 of them based on radial velocity, presence of H\( \alpha \) and/or Li absorption line (depending on mass). The \( I_m \) vs. \( I_m-z \) color-magnitude diagram of the confirmed members is shown in Fig. 2, together with isochrones and the predicted location of the LDB from the evolutionary tracks of Baraffe et al. (1998). The figure shows a sharp boundary: the faintest star without a detected Li line has \( I_m = 16.39 \), while the brightest star with Li has \( I = 16.61 \). The LDB was determined as the mean of the two values, assuming \( d = 370 \) pc, and reddening \( A_I = 0.326 \). After considering all of the observational uncertainties, this yields \( M_I = 8.52 \pm 0.40 \). Accordingly, IC 4665 has an LDB age of \( t_{\text{LDB}} = 27 \pm 5 \) Myr. This value confirms the PMS nature of IC 4665 and agrees with the turn-off age, the first secure instance for a PMS cluster.
5. Theoretical Uncertainties in Evolutionary Tracks and Ages (Young)

The accuracy of stellar ages determined from fitting to evolutionary tracks or isochrones is limited by the accuracy of the tracks themselves. Inaccuracies can arise from missing or incorrect physics in the models as well as physical quantities known with limited precision, such as metallicity. Some of the most important sources of error are discussed here individually, but it is important to remember that there are cross terms between all of these quantities.

The most important problem is the hydrodynamics in stellar models. Because evolution calculations are treated as a series of snapshots of static states, dynamics are often ignored. Some elements such as rotation have been added, but are generally treated analytically and in isolation. Deficiencies are often corrected by the inclusion of free parameters calibrated by observations. A calibration appropriate for one stellar type is generally incorrect for others. As a result, mixing in stars in very poorly described and not predictive.

Convection is defined by thermodynamic gradients, which is appropriate only for the onset of convection. Once convection is established, the dynamically unstable part of the star is larger than the thermodynamically unstable region, and other processes besides convection can contribute to mixing. Evaluating the stability of the stellar stratification against all the available sources of kinetic energy, including turbulent convection, waves, and bulk rotational flows gives a self-consistent and predictive description of the hydrodynamics. Differences from standard models can be large, especially for massive stars. Larger mixed regions result in higher luminosities, larger radii, efficient angular momentum
transport, and transport of chemical species to the photosphere. On the MS model ages for a sample of eclipsing binaries from 1 to 23 \( M_\odot \) change by 15–400%. Radiative transport can be important for stars with deep convective envelopes. The diffusion time of energy from a fluid parcel can become comparable or even less than the crossing time of the convection zone. Convection becomes very inefficient, leading to larger radii, and ages can differ by 10’s of %.

Even complete and correctly implemented physics can cause problems due to the inherent lack of precision in our determination of physical quantities. A comparison of the OPAL and Timmes & Arnett (1999) equations of state (EOS) gives surprising results. The two formulations differ by at most 2% under any of the conditions tested, yet they produce very different radii on the Hayashi track. Ages determined from each model can vary by ~60% or so. The main sequences are not reconcilable without changing the composition or convective treatment. This is likely the largest source of uncertainty for sub-solar mass tracks.

Composition, unsurprisingly, plays a significant role. For a 10% change in composition, deeply convective stars can have ages different by ~10%, while MS ages can change by factors of several. Given that determinations of the solar composition have changed by roughly a third in five years, this is a serious problem, especially when precise metallicities are unavailable for most stars.

The conversion to observables adds another layer of complexity beyond the scope of this discussion. Model atmospheres, temperature to color conversions, rotational evolution (which require magnetohydrodynamics to model), and correct distances are all necessary.

So far we have discussed these sources in isolation. When matching model tracks, radius is the primary comparison, whether directly or through \( T_{\text{eff}} \). Individual effects drive radius in opposite directions, and so cannot be calibrated out. As a very simplified example of this interplay, consider a change in the equation of state. This changes the stratification of the star. A change in the stratification changes the extent and vigor of convection. Hydrodynamics enters to change the depth of convection and introduces new mixing processes that change the compositional structure and thus stratification of the star. These processes also transport angular momentum, which feeds back on the stability and mixing. These change shift opacities as well as solutions for the EOS. The problem must be solved self-consistently in order to reduce the uncertainties and produce an accurate result.

In short, hydrodynamics introduces changes of 10’s to 100’s of % in age determinations. Radiation transport adds 10’s of % on the Hayashi track. The EOS is a surprisingly large contributor at 10’s of % at 1 \( M_\odot \). Composition can be a large effect for relatively small changes. All of these sources influence each other. These cross terms can result in much larger synergistic errors, or, more insidiously, the right answers for the wrong reasons. Fortunately, multidimensional simulations are allowing us to understand and generalize the hydrodynamic processes in stars, resulting in a considerable improvement in the models.

6. Asteroseismological Constraints on Ages (Miglio)

Though the potential of solar-like oscillations as an effective tool to determine stellar ages has been known for years (e.g. Gough 1995), it is just recently
that, thanks to the improvement of observational techniques (see Bedding, this volume), the seismic modeling of bright nearby stars has become reality.

The uniqueness of a seismic inference of age resides in the fact that oscillation frequencies carry direct information on the structure of the central regions of the star. A well-known indicator of stellar age for MS stars is the so-called small frequency separation (\(\delta \nu\)) which, as shown by the asymptotic theory of stellar oscillations (Tassoul 1980), represents a probe of the sound speed in the energy-generating core. The evolutionary state of a star can also be inferred by other suitable combinations of frequencies (see e.g. Roxburgh & Vorontsov 2003) or, in the case of models of evolved stars, by the detection in the oscillation spectrum of modes of mixed pressure and gravity character (see e.g. Christensen-Dalsgaard, Bedding, & Kjeldsen 1995).

As an example of one of the first attempts to model solar-like stars including seismic constraints, we consider the visual binary system \(\alpha\) Cen that, thanks to the combination of precise “classical” constraints (masses, radii, chemical composition, luminosity) and the detection of solar-like oscillations in both components (Bouchy & Carrier 2002; Carrier & Bourban 2003; Bedding et al. 2004; Kjeldsen et al. 2005), has recently been the subject of several theoretical studies (see e.g. Thévenin et al. 2002; Thoul et al. 2003; Eggenberger et al. 2004; Miglio & Montalbán 2005). As predicted by Brown et al. (1994), the inclusion of \(\delta \nu\) in the modeling of the system allows one to significantly reduce the estimated uncertainty on the age of \(\alpha\) Cen. If the asteroseismic constraints are not included in the fit, a value of 8.9 ± 1.9 Gyr is found, whereas the inclusion of seismic constraints reduces the estimated age (and its uncertainty) to 5.8 ± 0.2 Gyr (see Miglio & Montalbán 2005).

The accuracy of such age estimates is limited, however, by the poor frequency resolution of current seismic data and, more importantly, by uncertainties in the physics included in the stellar models. Nonetheless, once precise seismic data will be available in observationally well-constrained targets (e.g. visual binaries), asteroseismology will also be able to go beyond the determination of global parameters, and directly test stellar models – not only adding precision, but also accuracy to the age estimates.

7. Gyrochronology (Barnes)

That the rotation of cool stars slows as a function of age was first put on a firm observational footing by Skumanich (1972). The wealth of observational data for cool stars in clusters with “known” ages gathered over the past decade can be used to construct a useful age estimator from measured stellar rotation periods (“gyrochronology”). More details about this can be found in Barnes (2003) and Barnes (submitted to ApJ).

Beyond an age of ~100 Myr, the rotation rate of any late-F to early-M star (those with surface convection zones and interior radiative zones) is describable by \(P = f(B-V) \times g(t)\), where \(P\) is the rotation period of the star, and \(f\) and \(g\) are separable functions of stellar color, \(B-V\), and age, \(t\), respectively. Both \(f(B-V)\) and \(g(t)\) can be determined purely from the data. From the open cluster data, one can show that \(f(B-V) = (0.773 \pm 0.011) \times (B-V_0 - 0.4)^{0.603\pm0.024}\). \(g(t)\) can be shown to be roughly Skumanich (Skumanich 1972), and by requiring that the solar rotation rate be reproduced at solar age, one finds that \(g(t) = t^{0.519\pm0.007}\).
The preceding considerations allow us to write the “gyro age” of a star as:
\[
\log(t_{gyro}) = \frac{1}{n} \left\{ \log(P) - \log(a) - b \times \log(B - V - 0.4) \right\},
\]
where \( n = 0.519 \pm 0.007 \), \( a = 0.773 \pm 0.011 \), and \( b = 0.601 \pm 0.024 \). One can also derive an error on the gyro age. The fractional error is given by
\[
\frac{\delta t}{t} = 2\% \times \sqrt{4.5 + \frac{1}{2} \left( \log t \right)^2 + 2P^{0.6} + \left( \frac{V - 0.4}{x} \right)^2},
\]
where \( x = B - V - 0.4 \). For late-F to early-M stars of \( \sim 1 \) Gyr, this works out to be \( \sim 15\% \).

This method satisfies all five criteria desired for an age indicator: of finding a variable that changes regularly and sensitively with age, of being able to calibrate that variable against a very well-defined age, or set thereof, of being able to identify and measure the functional form of the variable against its dependent variables (this one is even separable), of being able to invert the dependence to find the dependence of age on the other variables, and finally, of being able to calculate the error as a function of the variables.

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**References**

Amelin, Y., Krot, A. N., Hutcheon, I. D., & Ulyanov, A. A. 2002, Science, 297, 1678
Baraffe, I., Chabrier, G., Allard, F., Hauschildt, P.H. 1998, A&A, 337, 403
Barnes, S. A. 2003, ApJ, 586, 464
Bedding T. R., et al. 2004, ApJ, 614, 380
Bouchy F. & Carrier F. 2002, A&A, 390, 205
Brown T. M., et al. 1994, ApJ, 427, 1013
Carrier F., Bourban G., 2003, A&A, 406, L23
Christensen-Dalsgaard J., Bedding T. R., Kjeldsen H., 1995, ApJ, 443, L29
D’Antona, F., & Mazzitelli, I. 1997, Mem. Soc. Astro. It., 68, 807
D’Antona, F., & Mazzitelli, I. 1998, ASPC, 134, 442
Eggenberger P., et al. 2004, A&A, 417, 235
Gough D. O. 1995, ASPC, 76, 551
Jeffries, R. D. 2000, ASPC, 198, 245
Kenyon, S. J., & Hartmann, L. 1995, ApJS, 101, 117
Kjeldsen H., et al., 2005, ApJ, 635, 1281
Luhman, K. L. 1999, ApJ, 525, 466
Miglio A. & Montalbán J. 2005, A&A, 441, 615
Palla, F., Randich, S., Flaccomio, E., & Pallavicini, R. 2005, ApJ, 626, L49
Palla et al. 2007, ApJ, submitted
Roxburgh I. W., Vorontsov S. V., 2003, A&A, 411, 215
Sacco et al. 2007, A&A, in press (astro-ph/0611880)
Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593
Skumanich, 1972, ApJ, 171, 565
Stauffer, J. R. 2004, ASPC, 324, 100
Stauffer, J. R., Hartmann, L. W., & Barrado y Navascues, D. 1995, ApJ, 454, 910
Stauffer, J. R. et al. 2003, AJ, 126, 833
Tassoul, M. 1980, ApJS, 43, 469
Thévenin F., et al. 2002, A&A, 392, L9
Thoul A., et al. 2003, A&A, 402, 293
Timmes, F. X., & Arnett, D. 1999, ApJS, 125, 277
White, R. J., & Hillenbrand, L. A. 2005, ApJ, 621, L65
de Wit, W. J., et al. 2006, A&A, 448, 189