The Ages of Stars
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Some problems in studying the ages of stars

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Abstract. I list some questions and problems that have motivated this symposium, particularly with regard to single stars and low-mass stars.

Keywords. Galaxy: structure, Galaxy: disk, kinematics and dynamics, solar neighborhood, Hertzsprung-Russell diagram, stars: late-type

1. Motivation

The age of a star cannot be *measured*, not in the way we can measure mass or composition, the other key determinants of a star's physical state. I have always thought of the Vogt-Russell theorem as asserting that the state of a star is a function of its mass, composition, and *age*, but really it is just mass and composition. The composition of an individual star inexorably changes with age, due, for instance, to nuclear processes or diffusion, but age is not itself the direct agent of that change; age is not a force.

Yet a knowledge of age is essential, for age is how we place something on the time axis that runs through all of stellar evolution and nearly all of astrophysics. We start, of course, with the Sun – for which we can measure non-stellar material in the laboratory – and construct physical models that can reproduce all that we know (which is a lot, especially given what has come from helioseismology). We work from the Sun to other masses, and, especially, to ensembles of stars. With a star cluster, the precision with which we know vital parameters may be mediocre, but creating consistent models that can reproduce the entirety of the behavior of a large group with the same age and composition (we assume) allows those models to be tested in critical ways.

And so we work our way through a variety of means of estimating the age of a star or an ensemble. Each of these links in the chain has its own weaknesses, and in this short introduction to this symposium, I will list some of the questions and problems that come to mind in thinking about stellar ages.

2. Methods of age estimation for individual stars

Many of the scientific questions that motivated this symposium are centered on the ages of individual stars. For example: How old are the stars that we know to host planets? We may soon find planets around stars in clusters, but our major focus will remain on the nearest stars for obvious reasons. It should be seen as a challenge (and embarrassment) for us that our cosmologist colleagues can claim better precision for the age of the Universe than we can for the ages of the nearest stars. In order to understand the formation and evolution of our Galaxy, we need to be able to determine the ages of individual stars that may belong to the thick- or thin disk, or streams that have been captured from torn-apart dwarf galaxies. Any really unusual star begs for an age to be associated with it.

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Determining the age of an individual, isolated star is a frustrating and thorny problem. Doing so for an ensemble – even a rich cluster – is not easy either. As is shown elsewhere in this volume, some cluster ages are claimed to have uncertainties of $\sim$10%, but there are not independent tests to verify that accuracy, and it is systematic effects (reddening, metallicity, opacities, and so on) that dominate.

Through decades of painstaking effort, models have been constructed that reproduce the current state of the Sun and which also fit the considerable information we now possess on its interior properties (and yet questions can still remain on so basic a matter as the solar oxygen abundance). Given that confidence in our knowledge of the physics of the Sun, we can then understand the state and behavior of stars with different masses and abundances, especially when we have additional constraints, such as needing to match all the stars in a cluster at once. Doing this gives us confidence that we understand the essential physics of stellar structure and evolution.

Of particular interest are lower-mass stars, near and below 1 $M_\odot$, and in particular those found in the field or in small groupings. These objects pose their own problems. The main sequence lifetime at 1 $M_\odot$ is about 10 Gyr, and so such stars have ages spanning the entire age range of the Galactic disk; this makes them useful as a population to study that disk. The Sun itself, according to models, is slightly brighter and slightly warmer than when it first arrived on the Zero-Age Main Sequence (ZAMS) 4.5 Gyr ago. Much of that evolution in the H-R diagram has been nearly parallel to the ZAMS. In addition, main sequences for different metallicities lie on top of one another, and so there are several kinds of degeneracy in trying to determine the age of a solar-type star solely from photometry and parallax.

The uncertainties inherent in almost all of the age-dating techniques are significant. Sometimes, however, the goal is not so much to arrive at precise ages for individual targets as it is to be able to reliably order and bin the targets in age (τ), or, more appropriately, in $\log\tau$. Many of the relationships that depend on age are power laws or exponentials, and so lend themselves to estimating $\log\tau$ more consistently than τ itself. Complicating the problem is the fact that the various indicators available to us all too often yield inconsistent results, or only limits in some cases, and combining the information into a single best judgment of age is not straightforward. The ages we will consider we place into four types: fundamental, model-based, empirical, and statistical. This order is from most reliable to least.

2.1. *Fundamental ages*

I regard an age as *fundamental* if the underlying physics is completely understood and well characterized. There is only one fundamental age, that of the Sun, and it is based on radioactive decay of meteoritic material. There remain some uncertainties in the chronology of the solar system (Chaussidon 2007), but in comparison to the problems faced with astrophysical ages they are minuscule. We take the Sun to be $4,567 \pm 5$ Myr old (Chaussidon 2007). This is the one and only stellar age that is both precise and accurate.

2.2. *Model-dependent ages*

We may think of the ages of clusters determined from their color-magnitude diagrams as being reliable, and they are probably the best we have, yet they depend inherently on our detailed knowledge of stellar physics. The next tier of age-estimation techniques all depend to some extent on models or very basic assumptions to work.

2.2.1. *Isochrone ages*

Ages determined from a star's position in an H-R diagram (HRD) are model-based. They are largely self-consistent, at least, and on the whole are probably reliable, but there are many steps involved in applying our knowledge of physics to the problem, adding uncertainty and model dependency. Not all models give the same answers, and this is especially true for pre-main sequence (PMS) stars because of our poor knowledge of how to treat convection.

For low-mass stars, the difficulties of placing stars in an HRD primarily arise from their very slow evolution. Just placing a star on a given set of isochrones implies both precise and accurate knowledge of a star's temperature, luminosity, and metallicity. Despite decades of effort, our ability to determine the $T_{\rm eff}$ of a star is still limited to about 50–100 K (Clem *et al.* 2004; Ramírez & Meléndez 2005; Masana *et al.* 2006), which is a substantial uncertainty (with the Sun again being a notable exception). To derive luminosities, we need good parallaxes, which are now available for the nearer stars, and also bolometric corrections. Our ability to determine metallicities has improved substantially, but they still remain somewhat model-dependent, uncertain, and inconsistent. We do have the advantage, sometimes, of working on stars like the Sun, so that spectrum features are abundant and narrow, and we can work differentially relative to the Sun and so reduce some systematic uncertainties. Gustafsson & Mizuno-Wiedner (2001) have noted potential problems with isochrone ages, based on uncertain knowledge of stellar interiors, but they are concerned with thick-disk and halo stars that can have overall abundances and abundance patterns that are very different from solar. For most field stars, the differences from solar conditions are fairly minor.

For clusters, a number of presentations at this symposium were included to address concerns such as the adequacy of current models. In addition, these questions arise:

- Can we determine key cluster parameters well- and reliably enough to further reduce uncertainties? Gaia should certainly contribute significantly.
- Can we establish $T_{\rm eff}$ scales and bolometric corrections for main sequence stars reliably and derive accurate luminosities? This is critical for understanding the scatter we see in CMDs and interpreting it as age spreads.
- Can we understand the atmospheres of ZAMS stars well enough to determine $T_{\rm eff}$ in the presence of high levels of activity?

The ages of PMS stars are also estimated from HRDs, but with some different problems. PMS evolution is rapid, and so isochrones are well separated, but the physics of PMS stars is still incompletely understood and different models can yield substantially different isochrones. The observed quantities – temperature and luminosity – are also harder to determine accurately for PMS stars. The accuracy of $T_{\rm eff}$ values is limited by the inherent variability of PMS stars and by their conspicuously inhomogeneous atmospheres; in other words, it is not straightforward to convert an observed color index into $T_{\rm eff}$. The same problems limit our ability to determine the luminosity, and, in addition, nearly all PMS stars are far enough away for the parallaxes to be not quite good enough, although that is being remedied. PMS isochrones are also metallicity-dependent, just as for the main sequence, but the same problems that inhibit our determining $T_{\rm eff}$ and luminosity (excess continuum emission and non-standard atmospheric structures that lead to line emission, among other things) also make accurate abundances problematic. Finally, precise and accurate masses for PMS stars are badly needed so that we can calibrate the evolutionary tracks. For the most part the masses of PMS stars are estimated from their position in an HRD, but few stars have measured masses. The few PMS stars in binaries that have measured orbits are critical tests of the models.

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For PMS stars, these questions arise:

- Can we test PMS models and isochrones well enough to have confidence in them? Perhaps the inconsistencies observed are in part due to the different models being applicable in different mass ranges? In other words, maybe all the models are partly right and partly wrong?
- Can we establish $T_{\rm eff}$ scales for PMS stars reliably and derive accurate luminosities? This is critical for understanding the scatter we see in CMDs and interpreting it as age spreads.
- PMS ages in particular are confused by the inherent uncertainty in the zero point. Can that be reduced or resolved?

2.2.2. *The lithium depletion boundary*

In recent years it has been possible to detect Li in the lowest mass members of some young groups and clusters and to then compare the location of the Li depletion boundary (LDB) to models. This method was proposed by Rebolo *et al.* (1992) and has now been used for several clusters. It promises to provide a sensitive indicator of cluster age (Bildsten *et al.* 1997) that is independent from that from the main sequence turnoff. However, the LDB ages for the three clusters studied by Barrado y Navascués *et al.* (2004), for example, are significantly higher than the turn-off ages (by about 50%), indicating a possible systematic effect.

At the present, LDB ages are attractive in that they involve many fewer assumptions than isochrone ages, but the age range for which the LDB can be used is small and so it has been difficult to test this method. The difficulties are worsened by the very-low-mass stars being so faint, even in the nearer clusters. More detections of the LDB in young clusters are needed.

2.2.3. *Ages from isotope decay (nucleochronology)*

Some ages determined from radioactive decay are model-dependent because they are for distant stars and there is a need to estimate the initial abundance of a species. Some of the Galaxy's older stars have had ages estimated from the decay of Th or U (Cayrel *et al.* 2001; Sneden *et al.* 1996; Gustafsson & Mizuno-Wiedner 2001; Kratz *et al.* 2004; Dauphas 2005; del Peloso *et al.* 2005a,b,c).

- Isotope-decay ages offer one of the only checks on the ages of old stars that is independent of isochrones and CMDs. Can we improve their accuracy?

2.2.4. *Asteroseismology*

In the past few years we have seen ages determined by matching stellar interior models to observed asteroseismological oscillation frequencies (Floranes *et al.* 2005). The underlying concept is that the lowest-frequency modes one can see in spatially-unresolved observations penetrate the core of the star, and the sound speed there is sensitive to the density, which is to say the helium fraction, which directly results from the star getting old. The results can be very precise, and they are accurate as well to the extent that the models are only modestly different from the solar models. For example, Eggenberger & Carrier (2006) determined the age of β Vir (an F8V star slightly more massive than the Sun) by this method, with age uncertainties of about 3 to 8%, although two separate solutions gave equally good fits to the observations. This asteroseismological method offers great potential for determining ages in ways independent of current techniques. It is particularly good for deriving the ages of older stars, which are also those most difficult to age-date in other ways. The observations to be obtained by the *Corot* and *Kepler* missions should be very important for this, and those asteroseismic ages can, in turn, help to calibrate better empirical age relations. At present there are not enough asteroseismic ages published to draw conclusions about them.

- The ages derived from asteroseismology depend on essentially the same physics as those from isochrones, but asteroseismologic ages will likely work best for older stars. Will the new generation of very large telescopes (30m) allow us to detect oscillations in solar-type stars in old clusters, so we can compare ages directly?

2.2.5. *Kinematic traceback ages*

On time scales of 10^8 to 10^9 years, stars and clusters in the Galactic disk encounter massive objects that disrupt their Galactic orbits; this leads to disk "heating" (see the reviews by Wyse and Nordström in this volume). This effect erases some of the past kinematic history of a star, but at very young ages these tidal encounters have not yet occurred and it is possible to trace back the Galactic motion of a star. When we find stars with common Galactic space motions, we can do this for them as a group and see when in the past they were in closest proximity. This is a simple application of mechanics but it involves assumptions about the Galactic potential. Blaauw (1978) appears to have been first to determine such an expansion age, and Brown *et al.* (1997) and Fernández *et al.* (2008) provide an analysis for a number of nearby OB associations that takes advantage of *Hipparcos* observations. The analysis of Brown *et al.* (1997) shows that although ages determined from kinematic traceback may avoid some model dependency, they are subject to significant systematic errors from a number of effects. These errors all conspire to make the association appear to be kinematically younger than its true age. As D. Fernández reports in this volume, these ages from kinematic traceback turn out to be unreliable.

2.3. *Empirical ages*

For the non-cluster stars, especially older ones, it is necessary to use predominantly *empirical* age indicators. In these cases we observe a relationship between the quantity and age that appears to be monotonic, and there is a reasonable scenario to account for much of what is observed. However, not enough is known about the underlying physics to calculate the way in which we believe the observed quantity ought to change with age. One of these indicators is the surface Li abundance. The others are all variations on the theme of the rotation-activity relation that has been so well studied during recent years.

There are three types of empirical age methods applicable to low-mass stars:

(*a*) The decline in surface lithium abundance.

(*b*) The loss of angular momentum and spindown of stars.

(*c*) The decline of magnetically-related activity with age, seen in such indicators as Ca II H and K, Hα, or x-rays.

All of these are discussed in detail in this volume, and each has its advantages, disadvantages, and useful range of ages and stellar masses to which it can be applied.

- Can we turn some empirical techniques into model-dependent ones? That would mean reaching an understanding of, say, rotational spindown in late-type stars, well enough to create models that predict stellar behavior. Despite our detailed knowledge of the Sun, we have not even been able to explain or predict the solar activity cycle, so the prospects for this seem poor.
- Will we ever really understand Li depletion? For every trend that is seen there always seems to be at least one exception. Recent work on stellar models (see Deliyannis in this volume) is at least encouraging.

2.4. *Statistical Ages*

Several properties of stars correlate with age, but there is not a one-to-one relationship that can be used to derive an age. Instead, only broad limits on the age can be set. For example, Galactic disk heating leads to older stars tending to have greater net space motions than younger stars. Indeed, the older populations of our Galaxy – the thick disk and halo – are defined by their large space motions. But disk heating is only a tendency, and it is easy to point out counterexamples to the trend: both the Sun and α Centauri are 4–5 Gyr old yet have low net space motions. Thus kinematics is at best suggestive of an age.

The so-called age-metallicity relation is even less useful in any practical way. It is not clear if an actual relationship exists between age and overall metallicity for the Galactic thin disk; what may appear as such may really be a relation between metallicity and the Galactocentric radius at which a star forms. For the stars of interest in this paper, none are old enough to even age-date very roughly from their metallicity.

- Is there really an age-metallicity relation or does it just seem that way because of other underlying Galactic trends?

3. Open clusters

Open clusters (OCs) would seem to present a best-case situation for estimating an age. Their overall abundances are generally close to solar, so the models applied can use well-tested physics. Several are close enough to have distances determined from trigonometric parallaxes. Reddening is generally low. Some are reasonably well-populated.

As an example, consider the Pleiades. It is nearby, making its members accessible to high-resolution spectroscopy. The precise distance to the Pleiades remains contentious despite efforts to measure the distance in a number of independent ways. All of those methods are consistent to within the stated uncertainties (Pinsonneault *et al.* 1998; Narayanan & Gould 1999; Gatewood *et al.* 2000; Stello & Nissen 2001; Makarov 2002; Munari *et al.* 2004; Pan *et al.* 2004; Zwahlen *et al.* 2004; Johns-Krull & Anderson 2005; Soderblom *et al.* 2005; Southworth *et al.* 2005) with the notable exception of the result from the *Hipparcos* mission, although the *Hipparcos* value (van Leeuwen 2007) has gradually approached the distances determined by other studies as corrections have been applied. The distances and metallicities of the nearby OCs are closely interrelated (An *et al.* 2007), so having independent measures of those quantities is vital.

Most of the Pleiades has only slight reddening ($E(B-V)=0.03$), although there are some patches with high reddening. It is fairly populous and photometry of excellent quality is available over the full range of stellar types from B to brown dwarfs.

Despite the importance and accessibility of the Pleiades, there have been few determinations of the cluster's metallicity: [Fe/H] $= -0.034 \pm 0.024$ (Boesgaard & Friel 1990); $+0.06 \pm 0.05$ (King *et al.* 2000); $+0.06$ (Groenewegen *et al.* 2007); $+0.06 \pm 0.02$ (Gebran & Monier 2008). Some other studies have looked at chemical peculiarities among the A stars, which we do not consider here. An *et al.* (2007) reanalyzed the data of Boesgaard & Friel (1990) and eliminated cluster non-members to get [Fe/H] $= +0.03 \pm 0.02$. Thus the average measured metallicity for the Pleiades appears to be $\sim 10\%$ supra-solar.

Quoted turn-off ages include: 78 Myr (Mermilliod 1981); 100 Myr (Meynet *et al.* 1993); 120 Myr (Kharchenko *et al.* 2005); 135 Myr (Webda database†); and 79 ± 52 Myr (Paunzen & Netopil 2006). The lithium depletion boundary age is given as 120–130 Myr (Stauffer *et al.* 1998) and 130 ± 20 Myr (Barrado y Navascués *et al.* 2004). We adopt

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† http://obswww.unige.ch/webda

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$\tau = 120 \pm 20$ Myr as an average, making the Pleiades an exemplar of a Zero-Age Main sequence cluster for intermediate-mass (about 0.5 to 2.0 $M_\odot$) stars. In other words, for one of the best-studied OCs available to us, the uncertainty in age is $\sim 20\%$. We should bear that uncertainty clearly in mind when we seek to estimate the ages of less-well-studied associations or young clusters.

OCs are critical in attempting to estimate the ages of individual stars because we rely on them as calibrators. This leads to a very basic problem. The majority of all OCs are no more than ~ 100 Myr old, and this is due to Galactic processes that rend them and strew their members into the field. This is where field stars come from and it means that there are few OCs at greater ages to test and calibrate age-estimation methods. Also, the rarity of old OCs means that they tend to be fairly distant and not so easily studied. Finally, the rarity of old OCs makes me wonder if the few that are left are truly representative of field stars of the same age. The old OCs that survive must have started out being rich and dense, which is unlike the star-forming regions we see in our part of the Galaxy. I can imagine, for instance, that a rich and dense OC might partition its internal angular momentum differently than a sparse cluster, leading to different distributions of apparent rotation. That is pure speculation, but we are often relying on rotation or a related quantity (activity) to estimate the age of an older star, and we use clusters such as M67 or NGC 188 to calibrate.

That leads to these questions about OCs and their ages:

- How can we improve OC ages, both in precision and accuracy? Eclipsing binaries can be very helpful if we are lucky enough to find a detached system near the cluster's turn-off so that we have well-determined masses, for instance.
- Can we at least rank-order clusters by age more reliably?
- Can we tell if there are real cluster-to-cluster differences in helium?
- Can we test the uniformity of composition for OCs?
- How can we tie field stars and calibrate empirical age indicators better?

4. Globular clusters

That basic assumption of uniform composition and age for a star cluster is now being shown to be problematic, especially for globulars. Questions about uniform composition in globulars have been raised for years. Among the most interesting and challenging astrophysical breakthroughs in recent years has been the discovery of multiple populations on the main sequences and turn-offs in old clusters (Bedin *et al.* 2004), both globulars and open clusters. The same considerations apply in studying nearby (resolved) galaxies and their populations, as discussed in several reviews herein:

- Can we accurately disentangle the various effects that have been put forth to explain multiple main sequences, such as different ages, different metallicities, or different helium abundances? Is there unambiguous evidence for multiple populations within globulars (i.e., stars formed separately and then merged, as opposed to various effects taking place within a globular after it forms).
- Are we considering all the options in trying to explain what's seen, or are there new classes of physical effects responsible?
- Can we reconcile the ages determined from a cluster turn-off with that from its white dwarf cooling sequence?

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At the symposium banquet in the historic Tremont Grand ballroom, Dave Soderblom insists that dinner not be served and the exits blocked until the situation with stellar ages is improved markedly.

William Noel, curator of manuscripts at the Walters Art Museum in Baltimore, shows the Archimedes Palimpsest to astronomers attending the “Ages of Stars” symposium.