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Asteroseismology of Stellar Populations in the Milky Way

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Andrea Miglio
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[1] http://www.sexten-cfa.eu/images/stories/conferenze2013/asteroseism/Asteroseismology_final.pdf.

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Part I
Introduction

Ages of Stars: Methods and Uncertainties

David R. Soderblom

Abstract Estimating ages for stars is difficult at best, but Galactic problems have their own requirements that go beyond those for other areas of astrophysics. As in other areas, asteroseismology is helping, and in this review I discuss some of the general problems encountered and some specific to large-scale studies of the Milky Way.

1 Why Care About Ages?

Much of what astronomers do in studying stars and our Galaxy explicitly or implicitly involves evolutionary changes: how things change with time, and the sequence of events. Yet time is not really a direct agent of change in stars, it is more a medium in which gradual changes occur. Because time is not a direct agent it leaves no direct indicators and we are left estimating age in mostly indirect—and so inexact—ways.

The problem is illustrated by considering the Sun. It is the only star for which we have a fundamental age, one for which all the physics is fully understood and all needed measurements can be made, and its age of $4{,}567 \pm 1 \pm 5$ Myr is both precise and exact. But the Sun itself tells us nothing of its age, and it is only from having Solar System material that we can analyze in the laboratory that such an exquisite result comes. For no other star can we do likewise.

Here is a scheme (from Soderblom 2010) for thinking about stellar ages, with five quality levels:

1. **Fundamental** age-dating methods, in which the physics is well understood and all the necessary quantities can be measured. The only fundamental age is that for the Sun just described.
2. **Semi-fundamental** methods that use well-understood physics, but which require some assumptions because not all the needed quantities are accessible to

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observation. These methods include nucleocosmochronology, for very old stars, and kinematic traceback, for young groups.
3. **Model-dependent** methods that, like most of stellar astrophysics, infer ages from detailed stellar models that are calibrated against the Sun. Model-dependent methods include fitting the loci of stars in clusters (especially the main sequence turn-off) and detecting the lithium depletion boundary (at the transition from stars to brown dwarfs for clusters and groups of stars), as well as isochrone placement and asteroseismology for individual objects.
4. **Empirical** methods that use an observable quantity such as rotation, activity, or lithium abundance that is seen to change with age but for which the physical mechanisms are not understood. Empirical methods are calibrated against model-dependent ages, generally by observing stars in open clusters. The paucity of open clusters older than $\sim 1/2$ Gyr makes calibrating empirical indicators problematic.
5. **Statistical** methods that rely on broad trends of quantities with age.

Before going further, I would like to narrow the discussion to methods relevant to Galactic problems as well as methods that produce useful results. First, in this context we are not interested in very young stars and so kinematic traceback, the lithium depletion boundary, and lithium depletion in general will be ignored. For a review about ages of young stars, see Soderblom et al. (2013). Second, nucleocosmochronology in principle is ideal for age-dating the very oldest stars in the Galaxy. It uses observations of isotopes of U and Th with long half-lives, but assumptions must be made about the starting abundances, generally done from other r-process elements. The results often differ by factors of two for the same star, and, in addition, the method needs excellent spectra of very high resolution to detect the weak U/Th features and so has been applied to only a handful of stars (Soderblom 2010). Third, there have been statistical studies of age-metallicity and age-velocity relations for the Galaxy, but they are at best very noisy relations that are hard to apply to individual objects, and in some cases their reality has been called into question. They will not be discussed further here.

2 Ages for Galactic Studies

There are both some special problems and potential advantages when it comes to estimating ages in order to understand the nature of our Galaxy. These naturally break down into two regimes based on the size scale being considered. In both cases one wishes to work with large samples of stars that can be selected with completeness or at least for which the biases are known. I will discuss small-scale samples (the solar neighborhood) as well as Galaxy-wide samples.

2.1 The Solar Neighborhood

Different studies use various concepts of "solar neighborhood" that depend on context. Here I will consider a radius of $\sim$ 100 pc. Within that distance, extinction and reddening are largely negligible; also there are only a very few clusters, and so field stars dominate. Solar-type stars (F, G, and K dwarfs) make an especially good population for studying this nearby portion of the Galaxy because they are reasonably bright and so identifiable within this sphere, and numerous enough to form a statistically useful sample. Also, the Sun has a main sequence lifetime of about 10 Gyr, and so G dwarfs are present from all epochs of star formation in the thin disk at least, and in the thick disk as well for late-G stars. Because they are similar to the Sun and have many narrow lines, G dwarfs yield abundances that are both more precise and more exact than for other stars. G dwarfs are amenable to age determinations in several ways. In particular, rotation and activity are known to decline with age, the problem being calibrating the relations, as described below.

The *Hipparcos* data make it easy to identify the G dwarfs within 50 pc, for instance, and there are about 3,000 stars from F8V to K2V, enough to make a useful statistical sample. Because *Hipparcos* was brightness limited, there are some biases in its sample: The sample favors binaries, and the completeness horizon diminishes in going to later spectral types, leading to smaller sample sizes.

2.2 The Galaxy as a Whole

If we want to delineate the structure of our Galaxy we need to use inherently luminous stars that occur everywhere and which can be seen at the far reaches, even when extincted. Red giants and stars on the asymptotic giant branch (AGB) fit that description well. In addition, for Galactic studies it is not necessary to always determine the ages of an entire sample, as one would like to do for, say, exoplanet hosts. Instead, Galactic work can be done in bulk with a finite failure rate as long as biases are known and can be controlled for. Finally, Galactic studies ideally need to determine stellar ages on an industrial scale, meaning 10,000 or more.

For these evolved, luminous stars, different age indicators are needed compared to the solar neighborhood sample. Rotation and activity are useless, as is isochrone placement because all the red giants pile up into a clump. But, as we will see, asteroseismology is very promising.

At intermediate distances (up to a few kpc), intermediate-mass stars can be helpful. Stars with main-sequence lifetimes of $\sim$2–4 Gyr (i.e., $\sim$1.5–2$M_\odot$) are promising because many are known and they evolve quickly enough to be placed on isochrones well.

3 Methods for Solar-Type Stars

The available methods of age-dating for solar-type stars are discussed in detail in Soderblom (2010) and here I will present only a brief synopsis with recent advances, particularly from asteroseismology.

3.1 Rotation and Activity

The trend of declining rotation with age for stars like the Sun has been known for some time (Skumanich 1972) and at least has a general scenario to explain it, if not a full physical model. In that scenario, it is the fact that the Sun carries energy through convection in its outer layers that leads to essentially all the aspects of the Sun that make it and similar stars "solar-like," and which make the Sun interesting. Convection and rotation—especially differential rotation—in the Sun's ionized outer layers interact to create a dynamo that regenerates a magnetic field. This field can grip an ionized stellar wind beyond the stellar surface and thereby transmit angular momentum to it, leading to spindown. Moreover, more rapid rotation produces a stronger magnetic field and thus more rapid spin down, leading to convergence in the rotation rates of a coeval sample that starts with a spread in initial angular momenta.

This convergence is seen, but it takes at least $\sim$ 500 Myr (i.e., the age of the Hyades) to occur at $\sim 1M_\odot$ and longer for lower masses. Until that convergence occurs, each star has its own rotational history and the large scatter seen among young stars in clusters makes it impossible to get an age from rotation.

Past the point of convergence it is assumed that stars obey the $\tau^{-1/2}$ relation (τ = age) of Skumanich (1972), but, in fact, we have only the Sun as a well-defined anchor point and so the relation is poorly calibrated. Adding additional uncertainty, it is possible for a star's companion to add angular momentum late in its life if, say, a close-in giant planet comes close enough to a star to have tidal effects or to even be consumed by the star, adding the orbital angular momentum of the planet to the rotation of the star, causing significant spin-up. Thus it is possible for some old stars to masquerade as young stars without revealing their true nature.

The situation for activity is worse because activity is an observed manifestation of the magnetic field, which is an indirect consequence of rotation. In addition, activity varies to some degree on all time scales, from flares and faculae, to rotational modulation by spots, to long-term activity cycles. As with rotation, the inherent spread in activity among young stars is large. It is possible to construct a mean activity-age relation (Soderblom et al. 1991) that looks good, but averages can hide a lot of inherent noise.

Activity can be fairly easy to measure, requiring spectra with R ~4,000 for the Ca II H and K lines, for instance, making it feasible to get data for many stars quickly. It is the interpretation of activity that is difficult and uncertain.