The time axis in stellar evolution

David R. Soderblom

Space Telescope Science Institute

1-410-338-4543

soderblom@stsci.edu

The problem

The time axis runs through all of astrophysics and is, of course, implicit whenever discussing stellar evolution. We want to know time-scales, and sequences of events, and the ages of stars. We can determine fairly good ages for clusters, so why is it important to be able to estimate an age for a single star? A number of key astrophysical questions depend on such ages:

- Sometime soon we can expect to detect an Earth-sized planet around a nearby field star. When we do we will want to know the age of that star as accurately as possible.
- Many of us hope to be able to detect signs of life on an Earth-sized planet around a nearby star. The means to claim such a detection are a discussion in itself, but an absolutely critical datum in interpreting a detection of life is the age of the parent star.
- In studying planetary formation and evolution in its early stages, we are naturally drawn to loose associations of pre-main sequence objects because of their proximity (such as β Pic, η Cha, TW Hya, etc.). A weak link in the chain of reasoning is the poorly-determined ages of these associations and the related problem of uncertain membership. These objects and groups are key to answering a questions as basic as "how long does it take for gas and dust to coalesce into planets?"
- The Sun and its behavior is rather important for our life on Earth, and some aspects of solar behavior may well contribute to global climate change. But the Sun itself can only tell us a small portion of its story – albeit a highly detailed story – because we see it for a brief instant in its life. To truly understand the Sun we need to provide context for it, and that comes from the stars. We would, ideally, like to create a solar comparison sample by finding stars of essentially the same mass, composition, and age and then observing the range of behavior they exhibit.

We all know the Vogt-Russell theorem: the physical state of a star is determined by its mass and composition. There are other details that also matter, of course (such as rotation, companionship, and the distribution of composition within the star), but mass and composition dominate. Age is implicit in the problem because the composition of a star steadily changes with age, especially while it is on the main sequence. The location of a star in an H-R diagram is predominantly determined by its mass, composition, and age.

Now, mass and composition can be measured, but age cannot. At best we can estimate a star's age. This is well illustrated by considering the case of the Sun. Because we can analyze non-solar material in a laboratory, we can measure the age of that material with great precision and accuracy (4,567±1 Myr). But we do not know exactly when the Sun formed relative to that clock.

In that case we are still left with only a small uncertainty. The next step is to extend solar physics – so well-calibrated from the detailed knowledge we have acquired of the Sun from helioseismology – out to the stars, and in particular to clusters. Having to construct models that work consistently across a broad range of masses constrains the problem, and yet even for the nearest open clusters we do not know the age to even 10%. For example, the Pleiades is fairly rich, has low reddening, and reasonably well-determined basic parameters such as distance and composition, yet its age is ~120±20 Myr, where the uncertainty has been determined from disagreement among various determinations.

Look at the challenge this way: Our cosmologist colleagues claim to know the age of the Universe to better precision that we can establish for the nearby stars or even for clusters. We should be able to do better than that.

How can we do better?

The need to determine more accurate and reliable stellar ages cuts across virtually all areas of stellar astrophysics. It is not the sort of problem that mandates its own singular effort or mission. Instead, consistent support of very basic stellar research is required.

Stellar theory and models are central to the effort. The better methods for determining ages are model-dependent and include fitting to isochrones, and analysis of asteroseismology. We can be hopeful that asteroseismology will come into its own and enable us to calibrate empirical age indicators (such as rotation, activity, and lithium abundance) when the results from the *Kepler* mission are analyzed. The current limitations of the models are evident when one sees significant differences in the ages of clusters from the isochrones calculated by different groups, and the conflict in ages from the main sequence turnoffs and white dwarf cooling sequences in some clusters. There is important physics of stellar interiors that we still do not understand.

Fundamental astronomy is critical too. Any stellar parameter that is measured to high accuracy serves to test the models; that includes diameters (from interferometry, for example). temperatures, luminosities, and distances. Effective temperatures, in particular, remain poorly determined.

The physics of age-related phenomena should be addressed. This includes the manner in which rotation and activity decline, or how lithium is depleted. Right now these are used strictly empirically, but if we could understand the physics we could go a lot further. If we could fundamentally understand the solar cycle, for instance, we would make significant progress in understanding how the interaction of convection and rotation leads to observable manifestations of activity and we could then hope to address the observed declines of rotation and activity with age from a physical standpoint, not just a heuristic one.

Every new frontier of precision forces us to go back and find the errors in the models that have been revealed. We are at a point where reliable stellar ages are critical for attaining our scientific goals.