some Age indicators

- GCs fitting MS, etc. (all old, but not all same age)
- White Dwarf Luminosity function
- Radioactive decay Thorium
- Isotopic ratios in interstellar grains

A main sequence star gets to burn about 12% of its initial mass in core H burning. During this time, it has an approximately constant luminosity. Hence the location of the main sequence turn-off point gives the age (to first order):

$$E \propto mc^2$$

$$L = dE/dt$$

H-burning efficiency

$$t = \frac{E}{L} = \frac{0.12(0.007)\,mc^2}{L}$$

This method depends on the distance scale, because $L \propto D^2$

horrible degeneracy

(a bigger Universe has brighter L so younger stars)

Age limits –

universe must be at least as old as its contents!

AGE PROBLEM: recall $t_h \leq H_0^{-1}$ $H_0 = 100 \rightarrow H_0^{-1} \simeq 10\,\mathrm{Gyr}$

Globular clusters

Chaboyer et al 1998 : $\langle t \rangle_{GC} = 11.5 \pm 1.3$ Gyr

Chaboyer et al 1992 : $\underset{\text{(oldest)}}{t_{GC}} = 17 \pm 2$ Gyr

local distance scale changed

common wisdom for a long time (since early 70s) : $t_{GC} = 15-16$ Gyr

very hard to imagine $t_{GC} < 12$ Gyr

MENTION ENERGY BUDGET

efficiency

– $$\underline{M_V^{TO} = 2.7 \log t_{GC} + 0.3\,[\mathrm{Fe/H}] + 1.41}$$ t_{GC} in Gyr

GCs typically very old (> 10 Gyr) & metal poor – $[\mathrm{Fe/H}] \approx -1.5$

(Fe/O different from solar

this is all distance dependent:

$$t_{TO} \propto \frac{M_{fuel}}{L} \quad \text{BUT} \quad L = 4\pi D^2 f$$

– $$V^{TO} - \overset{OR}{V^{HB}} = \Delta V = 2.70 \log t_{GC} + 0.13\,[\mathrm{Fe/H}] + 0.59$$

DISTANCE and EXTINCTION independent

weaker Z dependence

– $\Delta(B-V)$ not distance or [very] [Fe/H] dependent

but very hard to compute right in models

Radioactive Chronometer

r-process: very heavy elements synthesized in SN with very high neutron fluxes → creates elements far from nuclear "valley of stability"; long-lived isotopes persist.

Thorium decays with half-life of $t_{half} = 14.05$ Gyr which is an e-folding time $\tau = \frac{14.05}{\ln 2} = 20.27$ Gyr

measure Th/Eu in solar system with well known age (4.5 Gyr)
→ gives "initial" Th/Eu ratio (~0.46)

can then measure Th/Eu in very old star to get its age.
∴ depends on universality of initial Th/Eu ratio, which depends on nucleosynthesis site (type I, II, mix?)
BUT r-process abundance ratios remarkably similar in Sun and elsewhere, suggesting a universal initial ratio

$$N_{Th}(t) = N_{Th}(t_0)\, e^{-t/\tau_{Th}}$$

Observed in CS22892-052 : Th/Eu = 0.219
For solar system $N(t_0)$: Th/Eu = 0.46,

$$t = 15.2 \pm 3.7 \text{ Gyr}$$

Sneden (2003)
12.8 ± 3 ($^{Eu}/_{Th}$)
14.2 ± 3 ($^{r}/_{ss}$)

chemical evolution →

Chemical Evolution

assuming Thorium is produced at a constant rate per unit gas mass, r_{Th}

$$\dot{N}_{Th} = r_{Th} - \frac{N_{Th}}{\tau_{Th}}$$

so

$$N_{Th}(t) = r_{Th}\,\tau_{Th}\left[1 - e^{-t/\tau_{Th}}\right]$$

this corrects the initial solar value for the build up/decay of Thorium over time in the galactic disk:

$$N\left(\frac{Th}{Eu}\right) = \left(\frac{t_d - t_\odot}{\tau_{Th}}\right)\left(\frac{e^{\frac{t_\odot - t_*}{\tau_{Th}}}}{1 - e^{-\frac{t_d - t_\odot}{\tau_{Th}}}}\right) \cdot N_\odot\left(\frac{Th}{Eu}\right)$$

or
whatever:
want stable
~~r-process~~
nuclide

t_d = age of disk
$t_\odot$ = solar age

Answer depends on details of star formation history, but generally tends to increase inferred age.

White Dwarf luminosity function

$AGE = t_{WD} + t_{MS} + t_{form}$ ⟵ time to form galaxy, stars, etc.

↖ Main sequence life of progenitors of coolest WDs $(\sim 0.3\ \mathrm{Gyr})$

↗ time it takes to cool to faintest observed WD $\sim 9\ \mathrm{Gyr}$

gives age of galactic disk in <u>solar neighborhood</u> : $\approx 10\ \mathrm{Gyr}$

WDs just cooling, so form sequence $L \propto T^4$ roughly parallel to MS

computation of WD LF complex

depends on composition C/O He

& atmosphere ...

lots of number crunching details, said not to affect answer strongly (hmm...)

Other complications:

If composition includes some heavier elements, these will settle gravitationally providing an additional heat source.

e.g., 1% of mass in Ni would add ~ 1 Gyr to LF results

Some claims to rule this out through asteroseismology

Also have to worry about optical transport through WD atmospheres. If flux redistribution in cool stars makes them bluer (as in brown dwarfs) then this provides a wrinkle that could add ~ 1 Gyr

Age estimate from Oxygen isotopes in stardust

Oxygen made in moderate mass stars and dredged up from core during red giant phase. Isotopic ratios ($O^{18}/O^{17}/O^{16}$) depend on mass and metallicity of producing star.

Grains from such stars are found in grains on hyperbolic orbits — clearly external to solar system in origin. Effectively identical grains found in inclusions in primitive meteorites — i.e. they were incorporated at the time of solar system formation

$$\text{AGE} = t_{\odot} + t_{mix} + t_{*} + t_{Z}$$

4.6 Gyr
been around since solar formation

$\sim 10^8$ yr
dynamical time mixing ≪ 1 Gyr. appropriate?

$f(M,Z)$
typically 4-5 Gyr, some cases > 6 Gyr

many of these stars already pretty metal rich when they formed & aged before sun was born.
Takes time to make those metals: ~ 4 Gyr

yields best estimate of age for the galaxy

$$t_G = 14.4 \pm 1.3 \text{ Gyr}$$

lots of pieces — all must contribute, probably significantly so at least one could have substantial systematic error (e.g. t_Z — seems hard to do, but metallicity does appear to have built up fast).