Globular Cluster Age-Dating: Chaboyer et al. 1998

Kareem El-Badry
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Big Picture

- In 1998, the age of the universe was still fairly uncertain.
- Most globular cluster studies found ages older than the age of the universe predicted from cosmology.
    - Chaboyer et al. 1996 find: “a lower limit of approximately 12 Gyr for the oldest GCs in our Galaxy...which, for a **flat matter-dominated model**, implies that $H_0 < 53$ km/s/Mpc, a value which is low compared to almost all observational estimates”
    - Chaboyer et al. 1998 (this paper) made globular clusters younger: lower-limit of 9.5 Gyr!

Well, this is awkward

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OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4]
PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2]
B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7]
R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4]
NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]
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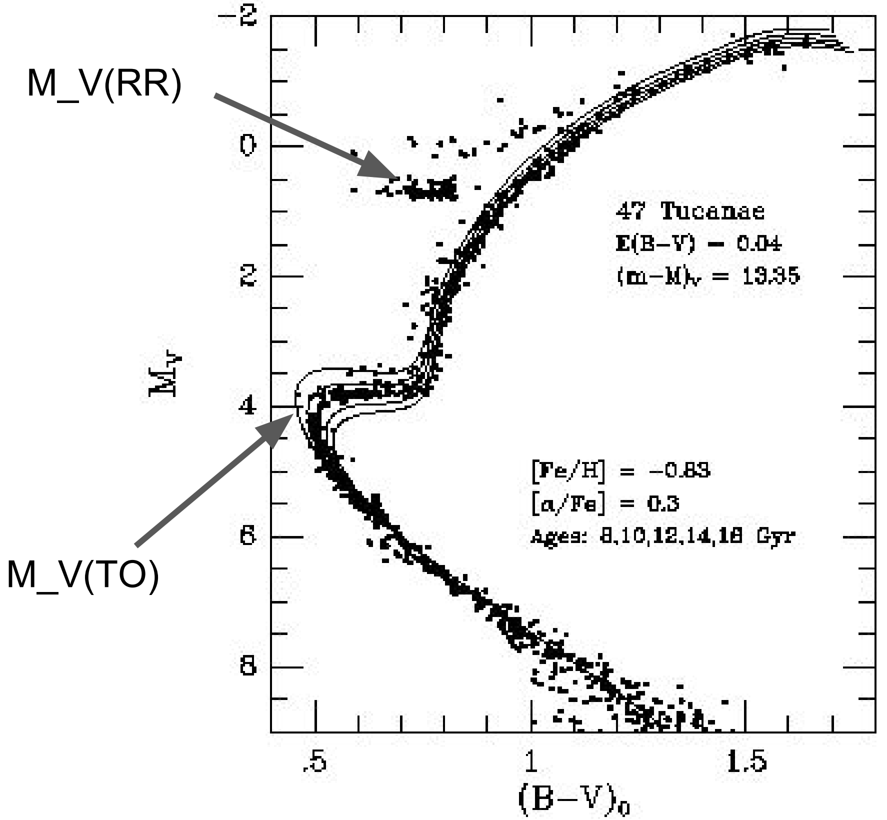
thods. We estimate the dynamical age of the universe to be 14.2 ± 1.7 Gyr including systematic

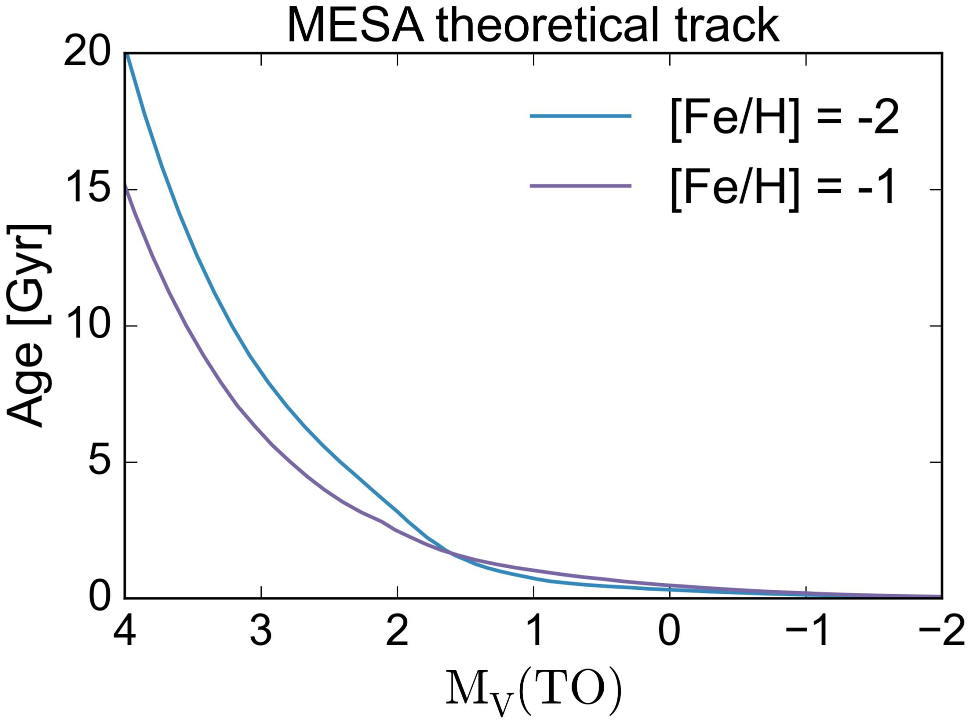
Ingredients for determining a GC's age

- GCs are SSPs, so all the stars should fall on a single isochrone.
- For a given metallicity, the main-sequence turnoff absolute magnitude (M_V(TO)) should be uniquely determined by age.



Idea:

1) Measure M_V(TO) from CMD.
2) Measure [Fe/H] from spectra of a few giants.
3) Use a plot like this →



Hmm… if you want < 1 Gyr accuracy, you’d better know M_V(TO) and [Fe/H] pretty accurately, and you’d better be confident in your models.

How to pin down M_V(TO):

- Problem: to know M_V(TO), you need to know distance.
- Solution: we (kind of) know M_V(RR).
    - M_V(RR) should be constant for ages > 7 Gyr (Chaboyer et al. 1996).
    - But it depends on metallicity, and you have to average over lots of stars (they're variable stars, after all).
- Measuring V(TO) - V(RR) is equivalent to measuring M_V(TO), if you can pin down M_V(RR).
- Measuring M_V(RR) is equivalent to measuring distance, if you know V(RR).

Lots of ways to measure M_V(RR). They all yield slightly different values.

TABLE 3

M_v(RR) CALIBRATION

Method	[Fe/H]	M_v(RR)	M_v(RR) at [Fe/H] = −1.9
Astrometric	−1.59	0.59 ± 0.11	0.52 ± 0.11
White dwarf fitting to N6752......	−1.51	0.45 ± 0.14	0.36 ± 0.14
Subdwarf fitting to N6752	−1.51	0.30 ± 0.15	0.21 ± 0.15
Subdwarf fitting to M5............	−1.17	0.54 ± 0.09	0.37 ± 0.09
Subdwarf fitting to M13	−1.58	0.36 ± 0.14	0.29 ± 0.14
LMC RR Lyrae......................	−1.90	0.44 ± 0.14	0.44 ± 0.14
Theoretical models	−2.20	0.36 ± 0.10	0.43 ± 0.10

Astrometric: compare internal proper motions to los velocities. Proper motions depend on distance; solve for distance.
White dwarfs: use white dwarfs as standard candles to get distance.
Subdwarf fitting: use magnitude of MS to get distance
LMC RR Lyrae: Get distance to LMC from Cepheids; compare Cepheid magnitudes to RR Lyrae.
Theoretical models: Stellar evolution calculations.

The model

Monte Carlo Input Parameters

Parameter	Distribution	Comment
Mixing length	1.85 ± 0.25 (stat.)	Fits GC observations
Helium diffusion coefficients......	0.3–1.2 (syst.)	Possible systematic error dominates
High-temperature opacities	1 ± 0.01 (stat.)	Comparison of OPAL and LAOL opacities
Low-temperature opacities........	0.7–1.3 (syst.)	Comparison of different tables
Primordial ^{4}He abundance	0.22–0.25 (syst.)	Possible systematic error dominates
Oxygen abundance [O/Fe]	+0.55 ± 0.05 (stat.) ± 0.20 (syst.)	Mean from Nissen et al. 1994
Surface boundary condition		Gray or Krishna-Swamy 1966
Color table		Green et al. 1987 or Kurucz 1992
Nuclear reaction rates:		
$p + p \to H + e^+ + \nu_e$ 2	$[1 \pm 0.002\ \text{(stat.)}^{+0.014}_{-0.009}\ \text{(syst.)}][1^{+0.02}_{-0.012}\ \text{(syst.)}]$	See Paper I
$^3He + {}^3He \to {}^4He + 2p$	1 ± 0.06 (stat.)	Bahcall & Pinsonneault 1992
$^3He + {}^4He \to {}^7Be + \gamma$	1 ± 0.032 (stat.)	Bahcall & Pinsonneault 1992
$^{12}C + p \to {}^{13}N + \gamma$	1 ± 0.15 (stat.)	Bahcall 1989, Table 3.4
$^{13}C + p \to {}^{14}N + \gamma$	1 ± 0.15 (stat.)	Bahcall 1989, Table 3.4
$^{14}N + p \to {}^{15}O + \gamma$	1 ± 0.12 (stat.)	Bahcall 1989, Table 3.4
$^{16}O + p \to {}^{17}F + \gamma$	1 ± 0.16 (stat.)	Bahcall 1989, Table 3.4

Generate lots of different isochrones at each age and metallicty by varying stellar evolution parameters within their uncertainties.

For theoretical isochrone of different ages and metallicities, calculate M_V(TO) - M_V(RR). Fit a function relating age, metallicity, and M_V(TO) - M_V(RR).

Uncertainty in stellar models is folded into uncertainty in coefficients.

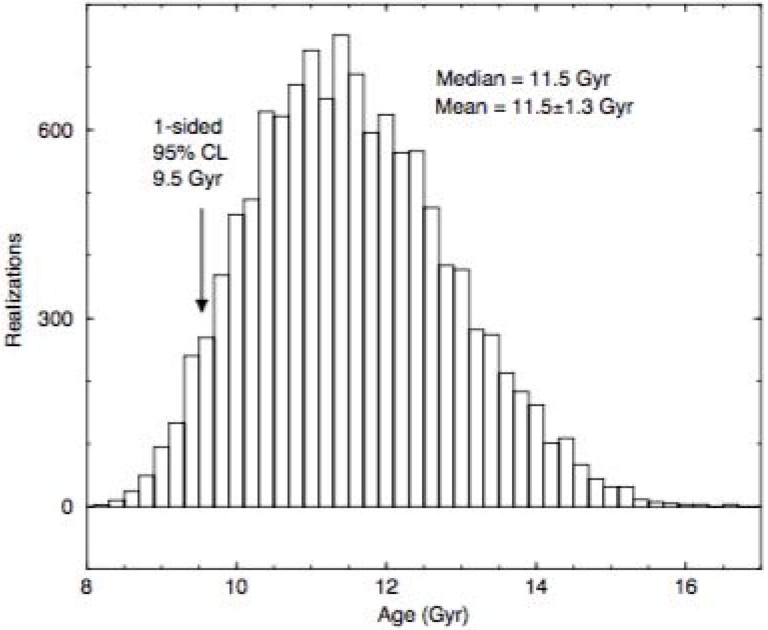
For an observed GC, plug M_V(TO) - M_V(RR) and [Fe/H] into this equation to calculate age.

grid of predicted ΔV_{HB}^{TO} values as a function of age and [Fe/H] that is then fit to an equation of the form

$$t_9 = \beta_0 + \beta_1 \Delta V + \beta_2 \Delta V^2 + \beta_3 [Fe/H] + \beta_4 [Fe/H]^2 + \beta_5 \Delta V [Fe/H] , \qquad (2)$$

where t_9 is the age in Gyr. The observed values of ΔV_{HB}^{TO} and [Fe/H], along with their corresponding errors, are input into equation (2) to determine the age and its error for each GC in our sample.

Varying model parameters within their uncertainties yields errors on ages as well.



As expected, age estimates are highly dependent on M_V(RR). Also some dependence on stellar models.