Why do globular clusters have more than one main sequence?

Ref: Gratton et al. 2012, A&ARv, 20, 50
1st, a pretty picture...
Outline

- The lives of stars
  - Some basic physics
- Importance of clusters
  - Globular clusters are really, really old!
- GC details
  - Observations
- GC details
  - Models and formation
What do we know about stars?

- They are born
- They live
- They die
- They spread their seed
Stars appear in groups
Modeling a Star

Four coupled first-order differential equations describe stellar structure

\[
\begin{align*}
\frac{dP(r)}{dr} &= - \frac{GM(r) \rho(r)}{r^2} \\
\frac{dM(r)}{dr} &= 4\pi r^2 \rho(r) \\
\frac{dT(r)}{dr} &= - \frac{3L(r) \kappa(r) \rho(r)}{4\pi r^2 4acT(r)^3} \\
\frac{dL(r)}{dr} &= 4\pi r^2 \rho(r) \varepsilon(r)
\end{align*}
\]

\[
\begin{align*}
M(r = 0) &= 0 \\
L(r = 0) &= 0 \\
P(r = r_*) &= 0 \\
M(r = r_*) &= M_*
\end{align*}
\]
Physics of Stars

- Need a way to connect: pressure, opacity, and energy production.

Equation of State

\[
P = P(\rho, T, \text{composition})
\]

\[
\kappa = \kappa(\rho, T, \text{composition})
\]

\[
\varepsilon = \varepsilon(\rho, T, \text{composition})
\]

Opacity

\[
\bar{\kappa}_{bf, ff} \approx \frac{\rho}{T^{3.5}}
\]

Energy generation

\[
\varepsilon = \frac{2^{5/3} \sqrt{2}}{\sqrt{3}} \frac{\rho X_A X_B}{m_H^2 A_A A_B \sqrt{\mu}} Q S_0 \frac{E_G^{1/6}}{(kT)^{2/3}} \exp \left[ -3 \left( \frac{E_G}{4kT} \right)^{1/3} \right]
\]
Star clusters

Globular Cluster

Open Cluster
Our ideas of stellar evolution came about because of the single population theory of cluster formation.

But there are still some outstanding issues:
- Blue stragglers
- Mass loss
- AGB stars
- White dwarf cooling
Why are clusters important?
Overview of star formation

- Trigger
- Gravitational collapse
  - Heating/ rotation/ magnetic fields slow collapse
- Eventual H-fusion
  - Main sequence star
Globular clusters

- Spherical collection of gravitationally bound stars
  - > 100,000 stars
- The Milky Way has about 200
- GCs are found in all galaxies of large size
Other galaxies

- M87
- More than 10,000 GCs
  - Many visible in this image
1 Main sequence

- Photometric narrow MSs
- Proof of single-age
- Single metallicity

- Until...
47 Tuc

16,700 ly away
120 ly across

$M_V \sim 4.9$

~ full moon size
47 Tuc

- Single MS?

Cannon et al. 1998
47 Tuc

- Anti-correlation between CN and CH molecular bands
47 Tuc

- Why is this impressive?
- Primordial in origin
  - Giant stars can mix N
  - MS stars can not!
- Anticorrelations between O and Na & Mg and Al
  - Low mass stars do not make Na
  - Nor do they destroy Mg
- Clear indication of external origin
$\omega$ Cen

15,800 ly away
180 ly across
$\sim$ million $M_{\text{suns}}$

Core stars .1 ly from each other
ω Cen

- 2 or 3 MSs

Bedin et al. 2004
NGC 2808

Typical GC

31,000 ly away

~12.5 Gyr old
NGC 2808

- Triple MSs

Piotto et al. 2007
Not just MSs

- Red giant branches of HR diagrams contain multiple populations of stars
- Horizontal branches of HR diagrams too.
GC Formation

- Understanding of the multiple population phenomenon has changed
  - Originally
    - Few peculiar clusters
    - Only massive clusters
  - Now
    - Probably all GCs have multiple populations
If 1-population theory wrong...

- GCs formed within large episodes of star formation in Giant Molecular Associations
- Scenarios include several generations of stars
  - Primordial, first, second...
- We observe second generation now
  - First generation “polluted” the second
4 additional mechanisms to consider

- Original homogeneities in the primordial material
- Peculiar evolution of stars
- Merging of GCs
- GC pulling in interstellar material (“pollution”)
A possible model

- N-body & hydro. simulations

- 1\textsuperscript{st} generation AGB star’s ejecta flows to GC center

- 2\textsuperscript{nd} generation forms with “different” metallicity
  - Concentrated at center of GC

- Problem: IMF either uncommon or unknown
A sticky detail

- The polluting ejecta must be “diluted” by fresh gas
  - Mandatory part of the process

- Problem: how much of original gas went to 1st generation?
- Problem: how is pristine material gathered?
GC - Milky Way connection

- Present day GCs smaller now
- Star loss during initial formation

- Problem: what role does dark matter play?
**Mass of GCs**

- GCs used to be larger
  - Original proto-GCs contained 50% of halo mass

- Of all stars in halo 1.2% are in GCs
  - Other 98.8% are free but are in a HUGE volume
Lingering questions

- Mechanisms of inhomogeneities
- Nature of polluters
- Nucleosynthesis mechanisms
- Origin of diluting material
- Reliable 3-D hydrodynamical models of formation
my Contribution

- I model 2 aspects of this problem
  - Mean opacities necessary for stellar evolution
  - Atmosphere models necessary for color-color diagrams
Example

- NGC 6752
- $M_V \sim 5.4$
- Age $\sim 11.8$ Gyr
- $\sim 17,000$ Lyr
2 atmosphere models compared

Another pretty picture...
dSphs?

- Are GCs just small dwarf spheroidal galaxies?
  - GCs are closer to main MW
  - GCs lost dark matter (dSphs did not)
  - GCs are compact
  - dSphs evolved in isolation (GCs are part of MW)