Lecture 24: Testing Stellar Evolution
Readings: 20-6, 21-3, 21-4

Key Ideas
HR Diagrams of Star Clusters
Ages from the Main Sequence Turn-off
Open Clusters
  Young clusters of ~1000 stars
  Blue Main-Sequence stars & few giants
Globular Clusters
  Old clusters of ~100,000 stars
  No blue main-sequence stars & many giants
Nucleosynthesis

Testing Stellar Evolution
The Problem:
  Stellar Evolution happens to billion-year timescales
  Astronomers only live for 10's of years (and we're impatient)
The Solution:
  Make H-R diagrams for star clusters with a wide range of ages

Star Clusters

Groups of 100's to 1000's of stars moving together through space
All stars in a cluster….

- are at the same distance, so it is early to measure their *relative* luminosities (so if one stars is 4x brighter than another, it will also be 4x more luminous)
- have the same age
- have the same chemical composition (that is, born with same amount of H, He, Fe, Ca, etc. in their gas)
- have a wide range of stellar masses

Snapshot of stars of *different masses* look at the *same age* (and composition)!

Open Clusters

Sparse Clusters of 100's -1000's of stars
Few parsecs in diameter

Many blue M-S stars
A few giants
Many of them have young ages (100's of Myr), although there are some with ages of 10 Gyr

Globular Clusters

Rich spherical clusters of 10^5-10^6 stars
10-30 pc in diameter
No blue M-S stars
Many giants
Old Ages (8-13 Gyr)

The Main Sequence, Revisited

The Main Sequence is a Mass Sequence
- High-mass stars are hot and have high luminosities
- Low-mass stars are cool and have low luminosities

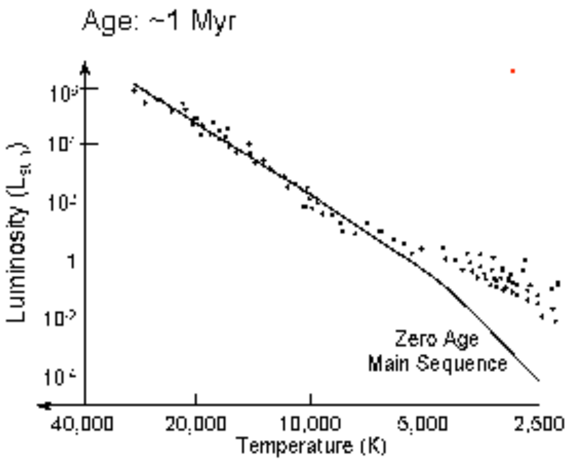
Main Sequence Lifetime depends on Mass (t_{ms}= constant/M^3)
- High mass stars have short M-S lifetimes
- Low-mass stars have long M-S lifetimes

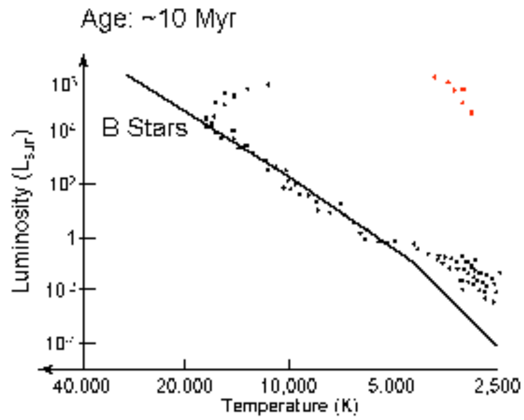
Low-Mass stars take longer to form (to go from protostar to M-S) than high-mass stars.

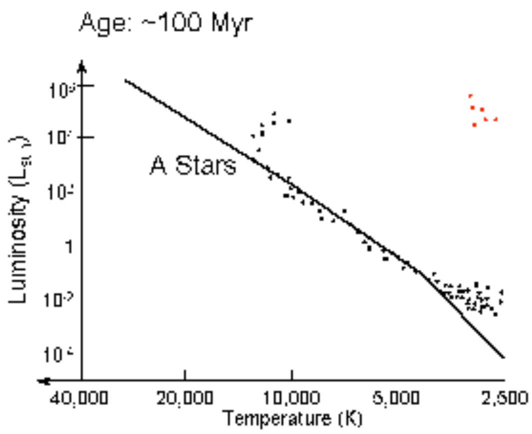
Progressive Evolution

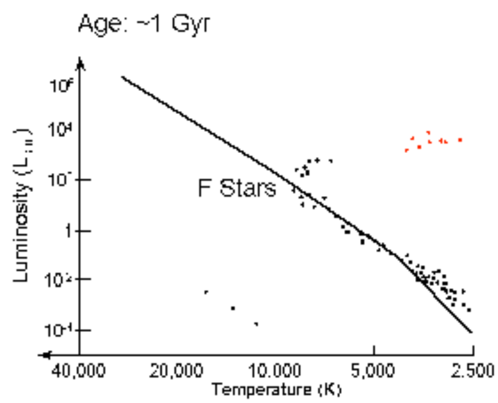
As a cluster ages:
- High-mass stars reach the M-S first, with the low-mass stars still approaching
- High-mass stars run out of hydrogen in their cores first, evolving into supergiants.
- As successively lower mass stars run out of hydrogen in their cores, they too evolve off of the M-S.

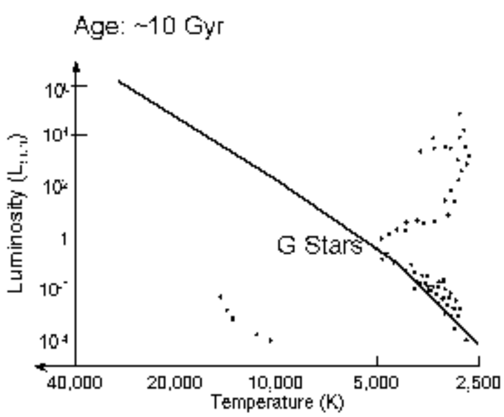
Stars peel off the Main Sequence from the top of the sequence (high-mass end) on down as the cluster ages.











Main Sequence Turn-off

Point where the Main-Sequence "turns off" toward giant stars

As the cluster ages, the stars at the turnoff are lower mass

Low mass stars have redder colors

Indicator of cluster age:

Older clusters have redder and less luminous turn-offs.
Exact age can be measured from the main-sequence lifetime for stars at the MSTO.

This is very obvious when we plot clusters with different ages on the same plot (note that we must know distances in order to do this).

Open Cluster H-R Diagrams

H-R Diagrams of Open Clusters show

They are young to middle-aged
Have blue M-S stars
Few supergiants or giants (stars spend very little time at this stage of evolution)
Older Open Clusters have more red giants
Don't see a horizontal branch, see the Hertzsprung gap instead
Youngest still have gas clouds associated

Globular Cluster H-R Diagrams

Very old ages: 8-13 Billion years
Red turnoffs and no blue Main-Sequence stars
Many Red Giants (low-mass stars spend as long as red giants as high-mass stars spend on the main-sequence)
No supergiants
A prominent horizontal branch (because low-mass stars spend hundreds of millions of years here)
Slightly bluer and fainter Main-Sequence due to having less metals (elements heavier than He) in their envelopes compared to nearby stars.

Conclusions of the Tests

Cluster H-R Diagrams give us a snapshot of stellar evolution

Observations of clusters with ages from a few Million to 15 Billion years confirms much of our picture of stellar evolution

Remaining challenges are in the small details, but the big picture is secure.

Nucleosynthesis

Nucleo tells us it has to do with nuclei
Synthesis – a complex whole formed by combining

Nucleosynthesis: the formation of heavy elements (heavier than H and He from the Big Bang)

Key Ideas

Neutron-Capture Processes
Stars Fuse and then Pollute
Enrichment of Planetary Nebulae and Supernova Remnants
Radioactive Decay in Supernova Remnants
Short-lived Radioactive Elements
- In asymptotic giant branch stars
- On earth

Old stars less enriched in heavy elements

Periodic Table of the Elements

Lots of elements, many more than the H and He that the Universe started out with.
Lots of elements heavier than the iron group (Fe, Co, Ni).

Making Elements Heavier than the Iron Group

^{56}Fe+^{56}Fe requires energy
^{56}Fe+n does not
- But
- Free neutrons are rare
  - Unless
  - Near a forming neutron stars (Type II SN=massive star SN)
  - In an AGB star where side reactions release neutrons

Adding neutrons is easy (if you have them) because they feel no electric repulsion.

This is critical for building up the heavier (heavier than iron group) elements because adding protons (if you have them) would require too much energy to overcome the electric repulsion.

Build up elements by ***NEUTRON CAPTURE***. Some of the neutrons will change to protons by radioactive decay and new elements will be formed.

Not a source of energy, but does make lots of interesting elements.

Neutron-Capture Processes

S(low)-process: add neutrons slowly, over 100,000s of years

Happens in asymptotic giant branch stars. The s-process makes a lot of zirconium, barium and lead.

R(apid)-process: add neutrons rapidly, over a few seconds

Happens in supernova? The r-process makes a lot of xenon, iridium, and all the uranium. Also makes tin, arsenic and gold, very useful for plots for movies.

The Fusion Story:

Stars have energy to shine for so long because they fuse elements in their interiors.

Low-mass stars:
  ($M < 4\ M_{Sun}$) fuse He, C, O and some neutron-capture elements via the s-process
  ($4\ M_{Sun} < M < 8\ M_{Sun}$) also Ne and Mg in addition to the above elements

High-mass stars ($M > 8\ M_{Sun}$)
  Fuse up to Iron group (Fe, Co, Ni) before SN explosion. Also fuse elements during shock wave passage through the envelope. Fuse elements up through Ni as well as some neutron-capture elements via the r-process (we think).
  Type II SN

White dwarfs
  Can exceed Chandrasekhar Mass by mass transfer from binary companion
  Runaway thermonuclear reaction and explode as a Type Ia SN

Fuse lots of Fe and Ni, little C and O, as those two elements are all burned to Fe and Ni.

Pollution of the Interstellar Medium (the gas between the stars)

Low-mass stars : Lose mass beginning with the red giant phase, but especially as planetary nebulae. A few low-mass stars may eventually explode as Type Ia SN.

High-mass stars: Mass loss as Red Supergiant
Type II SN explosion

Technetium in AGB stars

Tc is an element with no stable isotopes and the longest-lived isotope (^{98}Tc) has a half-life of 4.2 million years.

Models for AGB stars predict that Tc will be synthesized in the s-process and then transported by convection to the surface.

In 1952, Tc was detected for the first time in star and now is routinely found in the spectra of AGB stars. This is direct proof of nucleosynthesis in stars and a powerful verification of stellar models.

Technetium=Shiny

Planetary Nebula Enrichment

Planetary Nebulae have emission line spectra. Measurements of chemical composition in planetary nebulae reveal that they are rich in He, C, and O, in particular. Just as we expect.

Supernova Remnant Enrichment

Emission lines in Type II SN supernova remnants show that they are enhanced in iron, silicon and sulfur.

Radioactive Elements in Supernova

Originally the supernova is bright because the shock waves heat the envelope. As the envelope (now the remnant) cools and expands, the SN fades.

Fading slows at late times

The rate of fading of Supernovae (Both Type II and Type Ia) shows the large amounts of radioactive Ni (half-life=6 days) and Co (half-life=77 days) are produced.

Must have been made in the SN!

Short-lived Radioactive Elements on Earth

^{60}Fe has a half-life of 1.5 Million years
Detected in ocean crusts here on Earth
    Less than 50 atoms detected, but still detected
Where did it come from? It must have been made recently!
Evidence of a supernova exploding and polluting the Earth with a little bit of gas and dust
Supernova Characteristics:
    Distance ~ 30 pc
    Time ~ 5 million years ago

Chemical Composition

Stars spill guts
Interstellar gas enriched
New stars born that have more metals/hydrogen than before
Stars spill guts
REPEAT

Metals=elements heavier than helium, according to astronomers. For example, chlorine and neon=metals.

OLD STARS SHOULD BE POOR IN METALS

And they are!