LECTURE 11: STELLAR EVOLUTION. II. RED GIANTS

11.1 BECOMING A RED GIANT

After the core runs out of hydrogen, it contracts in order to stay hot (gravitational energy $\longrightarrow$ thermal energy).

With the rise in temperature, hydrogen begins to fuse in a hot shell surrounding the helium core.

As the core contracts and heats, the envelope (outer part of the star) *expands* and cools.

The star gets more luminous and redder. In the HR diagram it "ascends the giant branch."

11.2 STRUCTURE OF A RED GIANT

As a star becomes a red giant, the *average* radius goes down, but the radius of the *surface* goes up.

A red giant has an extremely dense core surrounded by a large, diffuse envelope.

The structure of a red giant is fundamentally different from that of a main sequence star, where the density and temperature rise smoothly from the surface to the center.

This difference in structure explains why red giants do not obey the same mass-luminosity relation and mass-radius relation as main sequence stars.

11.3 CORE-HELIUM FUSION

The helium core of a red giant contracts slowly, and it grows in mass as the hydrogen-fusing shell drops new helium onto it.

Eventually, the core becomes hot and dense enough to ignite helium fusion.

Helium fuses into carbon by the *triple-alpha process*. Roughly speaking, three helium nuclei (alpha particles) come together and fuse into a carbon nucleus, with beryllium as a brief intermediate stage.

Some carbon fuses with helium to make oxygen.

Helium fusion requires high temperature to overcome the electrical repulsion of helium nuclei and high density so that "triple collisions" can happen with reasonable frequency.

Helium fusion raises the temperature of the core, increasing its pressure, so it expands, and cools.

The luminosity of the hydrogen-fusing shell drops because of the lower temperature. Even though the star now has two fusion sources (helium core and hydrogen shell), its luminosity goes down somewhat.

11.4 MAIN SEQUENCE LIFETIMES

The lifetime of a star on the main sequence is

$$\text{lifetime} \ = \ (\text{nuclear energy supply})/\text{luminosity}.$$

The nuclear energy (on the main sequence) comes from hydrogen fusion.

If we assume that a star's supply of hydrogen fuel is proportional to its mass, and we use the approximate mass-luminosity relation $L \propto M^{3.5}$, we find

$$\text{lifetime} \ \propto \ M/L \ \propto \ M/M^{3.5} \ \propto \ 1/M^{2.5}.$$

More massive stars much more luminous, so they have shorter lifetimes even though they start with larger fuel supplies.

Stars with mass less than about $0.8 M_\odot$ have not evolved off the main sequence in the age of the universe.

11.5 THE HR DIAGRAMS OF STAR CLUSTERS

The stars in a star cluster are born at about the same time, so they are all about the same age.

The massive, hot, blue stars are the first to run out of core hydrogen and evolve off the main sequence (become red giants).

As the cluster ages, less massive stars run out of core hydrogen, and the main sequence "peels" down from the top.

In the HR diagram of a star cluster, the color of the *main sequence turnoff* (the bluest main sequence stars) is an indicator of the cluster's age. Older clusters have redder main sequence turnoffs.

The HR diagrams of open clusters and globular clusters look different primarily because all globular clusters are old, so they have no blue main sequence stars and lots of red giants.

Globular cluster stars have fewer heavy elements (metals) than open cluster stars, and this also makes some difference to the HR diagrams.

11.6 THE RED GIANT CLUMP AND HORIZONTAL BRANCH

While ascending the giant branch, a star's luminosity is constantly changing as the core contracts.

During core-helium fusion, the core does not contract, and the star's luminosity stays roughly constant for a relatively long time (nuclear energy $\longrightarrow$ thermal energy).

In open clusters, core-helium fusing stars have similar surface temperatures and form a "clump" in the HR diagram.

In globular clusters many stars lose parts of their outer envelopes. Core-helium fusing stars have similar luminosities but a range of surface temperatures. They form a *horizontal branch* in the HR diagram.

The core-helium fusing lifetime is shorter than the main-sequence (core-hydrogen fusing) lifetime because the star is more luminous and because helium fusion is less efficient than hydrogen fusion.

11.7 SUMMARY

When the core of a main sequence star has converted all of its hydrogen into helium, it contracts and gets hotter. Hydrogen starts to fuse in a shell around the core. The envelope expands, and the star becomes a big, cool, luminous, red giant.

Red giants have extremely dense cores and large, diffuse envelopes.

When the core of the giant becomes sufficiently hot and dense, helium begins to fuse to carbon and oxygen.

On the main sequence, more massive stars use up their fuel supply more quickly, so they have shorter main sequence lifetimes.

As star clusters age, they lose their most massive, bluest stars. The color of the main sequence turnoff indicates a cluster's age.

Giants with core-helium fusion form a clump in the HR diagrams of open clusters or a horizontal branch in the HR diagrams of globular clusters.