Summary of Lecture 19

Key points include:

1. Reminder: the main sequence for stars is when they are supported against gravity by the energy generated in the fusion of hydrogen to helium in the core.
2. But that core hydrogen doesn't last forever; what happens when it runs out?
3. The depletion of core hydrogen leads to a giant phase (where the star is highly luminous although comparatively cool, and is thus huge), and for most stars the ultimate fate is to end up small and dim although hot: white dwarfs.
4. The size range is gigantic: a white dwarf might be about the size of the Earth, a normal star could be the size of the Sun (about 100× the radius of the Earth), and a giant could be around 100× the radius of the Sun (and the full range of sizes of each type of star is substantially beyond these examples).
5. Why do stars become red giants? As the hydrogen in the core fuses to become helium, the helium "ash" builds up in the core. At that stage the core is not hot or dense enough to fuse helium, so the helium is inert: it doesn't produce energy. But the gravity of the star is still pressing down, so the remaining hydrogen has to fuse (or, informally, "burn", although this is nuclear fusion and not regular burning) faster to compensate. At some point the star undergoes a transition: the fusion rate in the core is so great that the outer layers expand tremendously and become cooler, as the core contracts and becomes hotter. This new equilibrium is a red giant: very luminous although cool, and therefore huge.
6. The sequence for a star like the Sun is therefore as follows. (1) After the star forms, it settles into the main sequence, where it holds itself up against gravity by fusion of H into He. (2) For a Sunlike star this will last about 10 billion years; lower-mass stars are on the main sequence longer, higher-mass stars are on the main sequence a shorter time. (3) The helium produced by fusion, which is inert, settles into the center of the core, leaving the outer part of the core as the part that is fusing hydrogen. (4) When it reaches a critical point, only an outer hydrogen "shell" is fusing, and the star expands to become a red giant. (5) Because the luminosity is much higher on the red giant phase than during the main sequence, the hydrogen that can be fused is used up much more rapidly during the red giant phase; this means that the red giant phase is comparatively short ($\sim$ few $\times\ 10^8$ years rather than the $\sim 10^{10}$ years for the main sequence, for Sunlike stars).

7. When the core hydrogen runs out, the core contracts and thus becomes hotter and denser. For many stars, the temperature and density can be great enough to start a new phase, of helium fusion. But the fusion of helium does not release as much energy as the fusion of hydrogen, and it requires higher temperatures and produces higher luminosities. The result is that the *helium main sequence* is much shorter than the normal (hydrogen) main sequence.

8. For low-mass stars such as our Sun, that's it; no more fusion in the core once the helium runs out. For higher-mass stars the situation is more exciting, as we'll learn later.

9. Because, in the red giant phase, the luminosity is high and the outer part (the *envelope*) is far away and loosely bound, a lot of the star's mass is lost as it is pushed away by radiation. This can lead to the removal of half of the mass, or more, to space. Sometimes this mass can be ejected to form a *planetary nebula*, so named because to early astronomers the ring of gas looked like a planet (but it actually has nothing to do with planets).

10. The remaining star isn't fusing, so it contracts to form a *white dwarf*, which is roughly the size of the Earth but can have 0.3 to 1.4 times the mass of the Sun. That means that a spoonful of white dwarf could weigh as much as a tank(!). This matter isn't held up by radiation, like normal stars. Instead, it is held up by what is called *degeneracy pressure*. It's a quantum mechanical phenomenon, and the basic idea is that particles such as electrons don't want to be near each other, so if you squeeze them to high density they repel and provide pressure. This doesn't depend on temperature: a white dwarf could be at absolute zero but its electron degeneracy pressure would still hold it up against gravity.

11. Thus low-mass stars end their lives as white dwarfs, cooling forever.

12. But electron degeneracy pressure can't hold up an arbitrary amount of mass. The limit, as discovered by the great Indian physicist Subrahmanyan Chandrasekhar and others, is about 1.4 times the mass of the Sun. Stars that begin their lives with less than about 8 times the mass of the Sun throw enough mass off during their evolution to end their lives under the Chandrasekhar limit. But what about heavier stars?