Chapter 12: Evolution of Low Mass Stars

- Sun won't remain a main-sequence star forever, eventually it will exhaust the hydrogen fuel source in its core
- relatively minor differences in the masses and chemical compositions of two stars can sometimes result in significant differences in their fates, two main categories of stars are high mass and low mass, luminous O and B stars follow a course fundamentally different from that of the cooler, fainter, less massive stars
- Low mass stars have masses less than 8 solar masses

12.1 The Life and Times of Main-Sequence Star

- structure of the Sun is determined by a balance between the inward-pushing force of gravity and outward force of pressure (maintained by energy released by nuclear fusion in core)
- more mass means stronger gravity, stronger gravity means higher temp and pressure in star's interior, higher temp and pressure mean fast nuclear reactions, which mean more luminous star
- stars with higher masses live shorter lives because they burn their fuel faster
- it would be unlikely for life to evolve on a planet orbiting a massive star with a stable life of only a few million years

- When the sun formed, 90% of its atoms were hydrogen, then it converted them to helium with the proton-proton chain
- As a protostar collapses, its always in balance, but it radiates away thermal energy, getting smaller and denser
- We can use the H-R diagram to observe a star's **evolutionary track** (as the protostars grow smaller and hotter until they reach their positions as stars on the main sequence)
- as a main sequence star uses the fuel in its core, its structure must continually shift in response to changes in its core composition; between the time the sun was born and the time it will leave the main sequence, its luminosity will have doubled (primarily during the last billion years of its life)
- mass and luminosity of main sequence stars are related, mass governs the rate at which nuclear reactions occur in the core, the time a star spends on main sequence is determined by its mass, less massive stars live longer
- at the temp found at the center of a low-mass main sequence star, atomic collisions are not energetic enough to overcome the electric repulsion between helium nuclei

- nonburning helium ash (products of fusion) accumulates most rapidly at the center of a star, chemical composition changes most rapidly at the center of a star and less rapidly as we move outward
- when the sun formed it had a uniform composition of 70% hydrogen and 30% helium by mass, but as hydrogen was fused into helium, the helium in the core climbed, now only about 35% of mass *in the core* of the Sun is hydrogen

12.2 A Star Runs Out of Hydrogen and Leaves the Main Sequence

- eventually a stars uses up its hydrogen fuel in the core, the innermost core is composed entirely of helium ash, thermal energy leaks out of the helium core into surrounding layers, no more energy in generated in the core to replace it, balance is broken, main sequence life has ended

- matter we usually experience is empty space; an atom is mostly empty except for space taken up by nucleus and electrons, this is just like the Sun--high temps strip electrons from nuclei through collisions, gas is ionized (a mix of electrons and atomic nuclei flying freely), but most of gas is still empty space, electrons and nuclei make up only a tiny fraction of volume
- when a low-mass star like the sun uses all its hydrogen at its center, the situation changes, gravity begins to overcome pressure, helium core is crushed, smaller and denser, finally reaches the limit of how many electrons can be packed in a given volume, so dense that a cubic centimeter has a mass of 1,000 kg, matter compressed to this point is **electron-degenerate**
- once hydrogen is exhausted, nuclear burning pauses in the core but continues outside of it, called **hydrogen shell burning** because hydrogen now burns only in a shell surrounding a core of nonburning helium and degenerate electrons
- rules of electron-degenerate matter: as more helium ash piles up, the core shrinks in size, so the more massive it is, the smaller it is; due to the added mass that increases the strength of gravity and weights bearing down on the core so electrons can be smashed further together
- degenerate core triggers a chain of events that will dominate the evolution of our 1 solar mass star for the next 50 million years after the hydrogen runs out
- degenerate core means stronger gravity, means higher pressure, means faster nuclear burning, producing greater and greater amounts of energy, this heats the overlying star layers, they expand to form a bloated, luminous giant, hundreds of times the luminosity of the Sun, a radius over 50 solar radii, yet the core is far more compact than the Sun's, and mass is only a few times the size of Earth
- as it gets larger and more luminous, it also gets cooler and redder due to the enormous expanse of its surface which allows it to cool easily, interior grows hotter, surface temp begins to drop
- H-R diagram helps keep track of changing luminosity and surface temperature as a star evolves away from the main sequence, as soon as a star exhausts its core hydrogen it leaves

the main sequence and moves upward and to the right on the H-R diagram, getting larger and cooler until progress ceases, surface layers regulate how much radiation can escape and so prevent it from getting cooler, so it moves vertically on the H-R diagram, grower larger and more luminous but maintaining the same temperature, it has become a red giant, this path has been the red giant branch of the H-R diagram

- change in structure is low at first, but the star then moves up the red giant branch faster and faster, takes about 200 million years to finish branch
- during first half, the luminosity increases to about 10 times that of the Sun, the second half, it rises to almost 1,000 times, like a snowball rolling down hill, the bigger it is the faster it rolls, but not exactly like a snowball because the helium core grows in mass not radius as hydrogen is converted to helium in the hydrogen burning shell, increasing mass of helium core increases gravity, pressure, then the rate of nuclear burning, core grows quicker

12.3 Helium Begins to Burn in the Degenerate Core

- in the degenerate core, although as many electrons are packed as possible, atomic nuclei are still able to move freely, as far as nuclei are concerned, the electron-degenerate core of the star is still mostly empty space
- as the star evolves up the red giant branch, the helium core grows not just smaller and more massive, also hotter, temp increase is due to gravitational energy released as the core shrinks and the energy released by the ever-faster pace of hydrogen burning in the surrounding shell, thermal motions of atomic nuclei in the core become more energetic until at 10^8 K, core helium nuclei collisions overcome electric repulsion and helium burning begins
- triple-alpha process: helium burns in a two-stage process, first, two helium-4 nuclei fuse to form a beryllium-8 nucleus with four protons, four neutrons, this nucleus is extremely unstable but if it meets another helium-4 nucleus within a trillionth of a second the two nuclei fuse into a stable nucleus of carbon-12 with six protons and six neutrons
- it's called triple-alpha because of the fusion of three helium-4 nuclei, known as alpha particles
- when helium in the core begins burning, degenerate material being a great conductor of thermal energy, evens out temperature differences in the core, in a few min the entire core is burning helium into carbon by the triple-alpha process
- pressure in gas comes from random thermal motions of atoms, increasing temp increases pressure, if helium core of red giant was a normal gas it would increase in temp from helium burning which would increase pressure, expand the core, temp/density/pressure/nuclear reactions would slow
- but degenerate core of a red giant is not normal; the pressure comes from density of electrons, heating the core doesn't change the number of electrons that can be packed into its volume, pressure doesn't respond to temp, and core does not expand
- higher temp doesn't change pressure but causes the helium nuclei to collide with more frequency and force, so nuclear reactions get stronger, temp rises, reactions get even stronger