What is a Star?

A star is a ball of gas held together by its own gravity. The force of gravity is continually trying to cause the star to collapse. This is counteracted by the pressure of hot gas and/or radiation in the star's interior. This is called hydrostatic support. During most of the lifetime of a star, the interior heat and radiation is provided by nuclear reactions near the center; this is phase of the star's life is called the main sequence. Before and after the main sequence, the heat sources differ slightly: before the main sequence the star is contracting, and is not yet hot nor dense enough in the interior for the nuclear reactions to begin. During this phase, hydrostatic support is provided by the heat generated during contraction; after the main sequence, most of the nuclear fuel in the center has been used up. The star now requires a series of less efficient nuclear reactions for internal heat, before finally collapsing when these no longer generate sufficient heat to support the star against its own gravity.

The Main Sequence

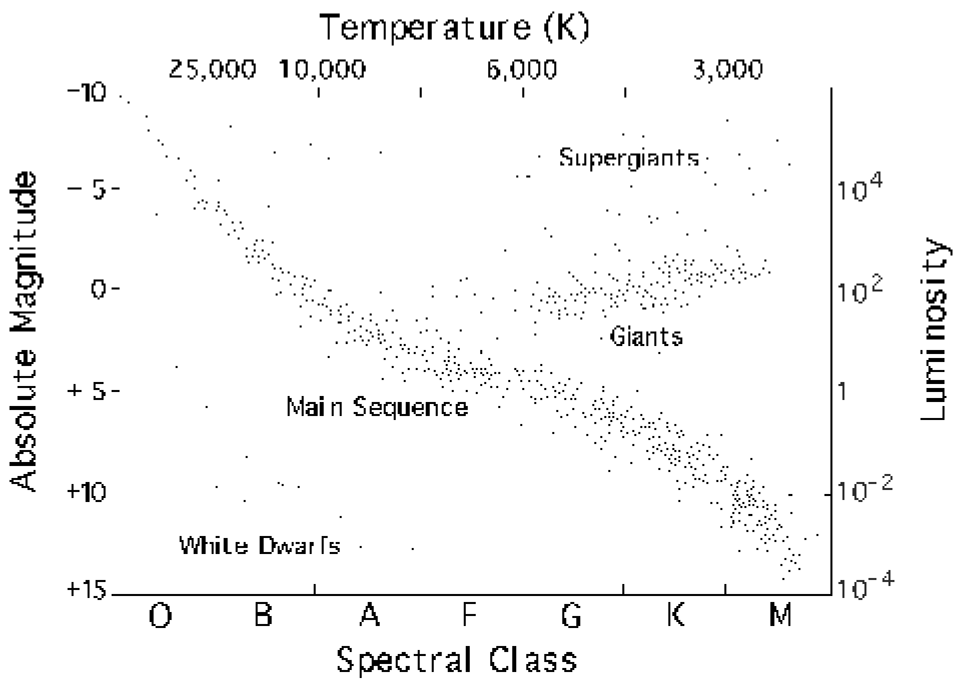
The properties of a main sequence star can be understood by considering the various physical processes acting in the interior. First is the hydrostatic balance, also called hydrostatic equilibrium. This determines the density structure of the star as the internal pressure gradient balances against the force of gravity. Another way of thinking about this is to imagine the star as a large number of nested thin spherical shells (sort of like an onion). The inward forces on each shell consist of the gravitational pull from all the shells inside it, and the gas and radiation pressure on the outside of the shell. The only outward force on each shell is the gas and radiation pressure on the inside of the shell; there is no gravitational force from material outside the shell (this is known as Gauss's theorem). In hydrostatic equilibrium, the inward and outward forces must balance. If they don't, the shell will either collapse or expand. The timescale for this to occur is called the 'free-fall timescale', and it is about 1000 seconds for a star like the Sun. Since we know the Sun has been more or less stable over the age of the Earth (several billion years), the hydrostatic balance must be maintained to a very high accuracy. A consequence of hydrostatic balance is that the pressure on each shell from material outside it must be less than the pressure from material inside it. This is because gravity acts only in the inward direction. Thus, the pressure in the star must decrease with increasing radius. This is an intuitively obvious result; the pressure at the center of the star is greater than it is at the surface.

The second physical process to consider is the transport of energy from the interior of the star to the edge. The interior of the star (that is, near the center) is heated by nuclear reactions, while at the surface of the star electromagnetic radiation can escape essentially freely into space. This situation is analogous to a pot of water on a stove, in which heat is deposited at the bottom by the stove burner, and is transported upward through the water to the surface where it can escape. The rate at which the water on the stove can transport the heat determines the temperature; a lid on the pot will cause the temperature in the water to be higher than it would be with no lid, since heat is impeded from escaping the pot. In the case of a star, the temperature of the gas determines the density structure via the hydrostatic equilibrium condition, so understanding the transport is important. The transport can occur by either of two mechanisms: either the energy is carried by radiation, or it is carried by convection. Radiation is the mechanism by which the Earth receives heat from the Sun, and its efficiency depends on the opacity of the material that the radiation must traverse. Opacity is a measure of the transparency of a gas, and it depends on the gas temperature, density, and elemental composition in a complicated way. Convection is analogous to the turbulent motion in a pot of water as it boils. It involves motion of the fluid in the pot (or the interior of the star) which transports heat. The operation of convection depends on how easily the gas can move, i.e. its viscosity and any forces (such as gravity) which tend to resist the convective motion. In addition, convection can only operate if it transports more heat than radiation. This turns out to be important! When the opacity is high (and radiation is inefficient), convection takes over. The details of the efficiency of convection are not well understood, and they are probably the major source of uncertainty in the study of stellar structure and evolution. A third energy transport mechanism, conduction, is relatively unimportant in stellar interiors.

Main sequence stars have zones (in radius) which are convective, and zones which are radiative, and the location of these zones depends on the behavior of the opacity, in addition to the other properties of the star. Massive stars (i.e., greater than several solar masses) are convective deep in their cores, and are radiative in their outer layers. Low mass stars (i.e., mass comparable to the Sun and below) are convective in their outer layers and radiative in their cores. Intermediate mass stars (spectral type A) may be radiative throughout. Convection is likely to be important in determining other properties of the star. The existence of a hot corona may be associated with active convection in the outer layers, and the depth of the convective layer determines the extent to which material from the deep interior of the star is mixed into the outer layers. Since interior material is likely to have undergone nuclear reactions, which change the elemental abundances, this mixing affects the abundances in the star's atmosphere. These can be observed by studying stellar spectra. They may also be ejected from the star in a stellar wind, and so affect the composition of interstellar gas.

The final ingredient in determining the structure of a main sequence star is the source of heat in the interior, nuclear reactions. There are many of these, and the details are complicated and there is still some uncertainty about the exact rates for the reactions (for example, the solar neutrino problem). The basic reactions which operate on the main sequence are fusion reactions which convert hydrogen nuclei (protons) into helium nuclei. These reactions require very high temperatures (greater than 10 million degrees) and densities (greater than 10,000 gm per cubic centimeter), and the rates are very sensitive functions of temperature and density. This is the factor which ultimately determines the lifetime of a main sequence star. More massive stars have greater central temperatures and densities and so exhaust their nuclear fuel more rapidly (in spite of the fact that they have more of it) than do lower mass stars. It turns out that the main sequence lifetime is a sensitive function of mass. For a star like the Sun the main-sequence stage lasts about 10,000,000,000 years, whereas a star 10 times as massive will be 10,000 times as bright but will only last 100,000,000 years. A star one tenth of the Sun's mass will only be 1/10,000th of its brightness, but will last 1,000,000,000,000 years. It is interesting to consider what would happen to the star if the nuclear reactions were to suddenly turn off. The timescale required for a photon released at the center of the star to make its way to the surface (via radiation or convection) is called the "thermal timescale" and is approximately 1000 years for the Sun. Thus, if the nuclear reactions were to turn off today, the Sun's luminosity would stay approximately constant for a long time by human standards. We do have historical records which tell us that the Sun's output has been approximately constant over the course of written human history, so we feel fairly confident that the nuclear reactions are still operating. However, there is the possibility that nuclear energy generation in the center of the Sun is not perfectly constant in time.

The three physical processes discussed so far, hydrostatic equilibrium, radiation transport, and nuclear energy generation, serve to determine the structure of a star. As with most things, the devil is in the details, and the areas of greatest uncertainty are the behavior of opacity and convection. These are active areas of scientific research.
A convenient way to characterize a star from observations is by its luminosity and its color. It is customary to plot these two quantities in an x-y plot, called a Hertzsprung-Russell diagram (after its inventors). It turns out that when this is done for main sequence stars with a range of masses, the points tend to occupy a narrow band in the diagram. The location of a main sequence star in the diagram depends only on its mass (see Figure below).



The Hertzsprung-Russell Diagram

Stellar Evolution

The mass of the star determines what happens after the main sequence phase. Stars similar in mass to the Sun burn hydrogen into helium in their centers during the main-sequence phase, but eventually there is not enough hydrogen left in the center to provide the necessary radiation pressure to balance gravity. The center of the star thus contracts until it is hot enough for helium to be converted into carbon. The hydrogen in a shell continues to burn into helium, but the outer layers of the star have to expand in order to conserve energy. This makes the star appear brighter and cooler, and it becomes a red giant. During the red giant phase, a star often loses a lot of its outer layers which are blown away by the radiation coming from below. Eventually, in the more massive stars of the group, the carbon may burn to even heavier elements, but eventually the energy generation will fizzle out and the star will collapse to a white dwarf.
Stars less massive than the Sun can have main sequence lifetimes greater than the age (so far) of the Universe. These may collapse into cool 'black dwarfs' following their main sequence lives.

There are very few stars with masses greater than five times the mass of the Sun, but their evolution ends in a spectacular fashion. They finish their main sequence lifetime in a way similar to the lower mass stars, but become brighter and cooler on the outside and are called red supergiants. Carbon burning can develop at the star's center and a complex set of element-burning shells can develop towards the end of the star's life. During this stage, many different chemical elements will be produced in the star and the central temperature will approach 100,000,000 K. During this stage, the structure can resemble an onion skin with progressive layers (going inward) dominated by elements with greater and greater atomic mass. This process ends when the core is composed primarily of iron. For all the elements up to iron, the addition of more nucleons to the nucleus produces energy and so yields a small contribution to the balance inside the star between gravity and radiation. To add more nucleons to the iron nucleus *requires* energy, and so, once the center of the star consists of iron, no more energy can be extracted. The star's core then has no resistance to the force of gravity, and once it starts to contract a very rapid collapse will take place. The protons and electrons combine to give a core composed of neutrons and a vast amount of gravitational energy is released. This energy is sufficient to blow away all the outer parts of the star in a violent explosion and the star becomes a supernova. The light of this one star is then as bright as that from all the other 100,000,000,000 stars in the host galaxy. During this explosive phase, all the elements with atomic weights greater than iron are formed and, together with the rest of the outer regions of the star, are blown out into interstellar space. The central core of neutrons is left as a neutron star, which could be a pulsar. This is remarkable since in the early Universe there were no elements heavier than helium. The first stars were composed almost entirely of hydrogen and helium and there was no oxygen, nitrogen, iron, or any of the other elements that are necessary for life. These were all produced inside massive stars and were all spread throughout space by such supernovae events. We are made up of material that has been processed at least once inside stars.

Explanation of Carina Nebula photo: In one of the brightest parts of the Milky Way lies a nebula where some of the oddest things occur. NGC 3372, known as the Great Nebula in Carina, is home to massive stars and changing nebula. Eta Carina, the most energetic star in the nebula was one of the brightest stars in the sky in the 1830s, but then faded dramatically. The Keyhole Nebula, visible near the center, houses several of the most massive stars known and has also changed its appearance. The Carina Nebula is about 7000 light-years away in the constellation of Carina. Eta Carina might explode in a dramatic supernova within the next thousand years, and has even flared in brightness over just the past two years.

This information was obtained from: http://www.nso.edu/sunspot/pr/mr_sunspot.html

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