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| The PleiadesThe Pleiades, a cluster of young stars  |

A star is a sphere of gas held together by its own [gravity](http://imagine.gsfc.nasa.gov/docs/dict_ei.html#gravity). The force of gravity is continually trying to cause the star to collapse, but this is counteracted by the pressure of hot gas and/or [radiation](http://imagine.gsfc.nasa.gov/docs/dict_qz.html#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, and this 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 enough or dense enough in its 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 core has been used up. The star now requires a series of less-efficient nuclear reactions for internal heat. Eventually, when these reactions no longer generate sufficient heat to support the star against its own gravity, the star will collapse. **The Main Sequence**The properties of a main-sequence star can be understood by considering the various physical processes occurring in the interior. First is the hydrostatic balance, also called hydrostatic equilibrium. This determines the [density](http://imagine.gsfc.nasa.gov/docs/dict_ad.html#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, resembling the structure of 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 (in physics, this is known as Gauss's law) 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 2,000 [seconds](http://imagine.gsfc.nasa.gov/docs/dict_qz.html#second) for a star like the Sun. Since we know the Sun has been essentially stable over the age of Earth (several billion years), the hydrostatic balance must be maintained to a very high level of 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, as the pressure at the center of the star is greater than it is at the surface.

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| [Sun PartsDiagram of a Solar-type Star](http://imagine.gsfc.nasa.gov/docs/science/know_l2/sun_parts.html)  |

The second physical process to consider is the transport of energy from the interior of the star to the surface. The interior of the star is heated by nuclear reactions, while at the surface 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 mechanism 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 Earth receives heat from the Sun, and its efficiency depends on the [opacity](http://imagine.gsfc.nasa.gov/docs/dict_jp.html#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](http://imagine.gsfc.nasa.gov/docs/dict_ei.html#elements) composition. 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 that tend to resist the convective motion, such as gravity. In addition, convection can only operate if it transports more heat than radiation. This is 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) that are convective, and zones that 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, which are those greater than several [solar masses](http://imagine.gsfc.nasa.gov/docs/dict_qz.html#solar_mass), are convective deep in their cores, and are radiative in their outer layers. Low mass stars, which have a mass comparable to or less than the Sun, 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](http://imagine.gsfc.nasa.gov/docs/dict_ad.html#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](http://imagine.gsfc.nasa.gov/docs/dict_ad.html#atmosphere). These can be observed by studying stellar spectra. They may also be ejected from the star in a [stellar wind](http://imagine.gsfc.nasa.gov/docs/dict_qz.html#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 events, but there is still some uncertainty about the exact rate of reactions. This is because the fundamental particles produced by nuclear reactions, called solar [neutrinos](http://imagine.gsfc.nasa.gov/docs/dict_jp.html#neutrino), react weakly with other particles. Most pass right through the planet, making them extremely difficult to detect.The basic reactions that operate on the main sequence are [fusion](http://imagine.gsfc.nasa.gov/docs/dict_ei.html#fusion) reactions, which convert [hydrogen](http://imagine.gsfc.nasa.gov/docs/dict_ei.html#hydrogen) nuclei (protons) into [helium](http://imagine.gsfc.nasa.gov/docs/dict_ei.html#helium) nuclei. These reactions require high temperatures (greater than 10 million degrees Celsius and densities (greater than a few hundred grams per cubic centimeter), and the rates are sensitive functions of temperature and density. This is the factor that ultimately determines the lifetime of a main sequence star. More massive stars have greater central temperatures and densities, and 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 billion years, whereas a star 10 times as massive will be 1,000 to 10,000 times as bright but will only last about 20 million years. A star with 1/10 the Sun's mass may only be 1/1,000 to 1/10,000 of its brightness, but will last about 1 trillion years. It is interesting to consider what would happen to the star if the nuclear reactions were to turn off suddenly. The timescale required for the energy from a [photon](http://imagine.gsfc.nasa.gov/docs/dict_jp.html#photon) released at the center of the star to make its way to the surface is approximately 1 million years for a star like the Sun. Along the way, the original gamma-ray photon interacts with the gas in the star and loses energy. Through multiple interactions like this, this energy "random walks" its way out of the star, ultimately being emitted at the surface as many photons in the ultraviolet and visual wavelengths. So, if the nuclear reactions were to turn off today, the Sun's [luminosity](http://imagine.gsfc.nasa.gov/docs/dict_jp.html#luminosity) would stay approximately constant for a long time by human standards. We do have historical records that tell us that the Sun's output has been approximately constant over the course of written human history, so scientists are 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.The three physical processes discussed so far — hydrostatic equilibrium, radiation transport, and nuclear energy generation — serve to determine the structure of a star. But the devil is in the details. The areas of greatest uncertainty are the behavior of opacity and convection, and these are active areas of scientific research.A convenient way to characterize a star from observations is by its luminosity, as well as its color, or temperature. It is customary to plot these two quantities in an x-y plot, called a Hertzsprung-Russell diagram. 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). HR Diagram |

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